Index-Based Assessment

	Segment A	Segment B	Segment C
Overal Rank:	**#1**	**#2**	**#3**
Average Likelihood:	**3.3**	**4.6**	**5.7**
Consequence:	**4**	**4**	**5**
Total Risk	**13.1**	**18.3**	**28.6**
Ext. Corrosion	**3**	**3**	**5**
Coating Condition	Good (somastic)	Average (heat damage, brittle FBE at the beginning)	Good-Average (replacing coating and pipe, ongoing, reduced operating temperature)
CP Efectiveness	Average (low CP spot exists)	Average (low CP spot exists)	Good
Atmospheric coating	Excellent	Excellent	good
Severity of Amonalies	<50%	<50%	<50%
Int. Corrosion	**3**	**5**	**5**
Product	Jet-A	Refined (mogas, diesel)	LSFO
Corrosion Monitoring	Yes	Yes	No
Inhibitors/Process Measures	No	Yes	No
Severity of anomalies	<50%	none	<15%
TPD	**4**	**4**	**5**
Depth of Cover	Over 3 feet	Over 3 feet	Under concrete, near RR, all developed
Signage	Adequate, line of sight	Adequate, line of sight	Adequate, line of sight
Row/Land Use	Utility coridoor, residential	Utility coridoor, residential	Agriculture, resorts
One-calls	1/week	1/week	1/quarter
Dents >2%	No new dents	No new dents	1 dent in 2005
PA Program	Effective	Effective	Effective
Incidents (damage, no one-call)	No	No	No

The Risk Matrix

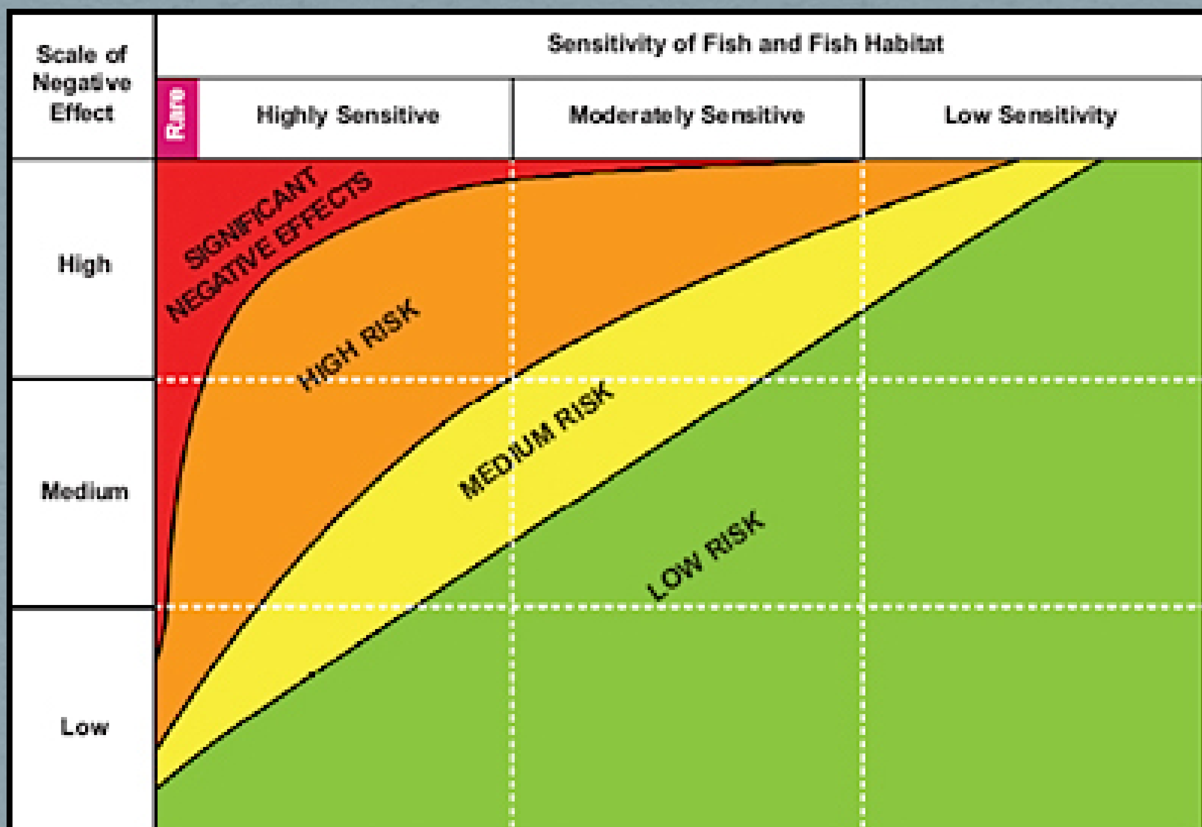
5	Very High	Decreasing Likelihood	5	10	15	20	25
4	High		4	8	12	16	20
3	Medium		3	6	9	12	15
2	Low		2	4	6	8	10
1	Very Low		1	2	3	4	5
Consequence Indices			Decreasing Consequence				
			Very Low	Low	Medium	High	Very High
			1	2	3	4	5

Marine Corps Risk Assessment Matrix

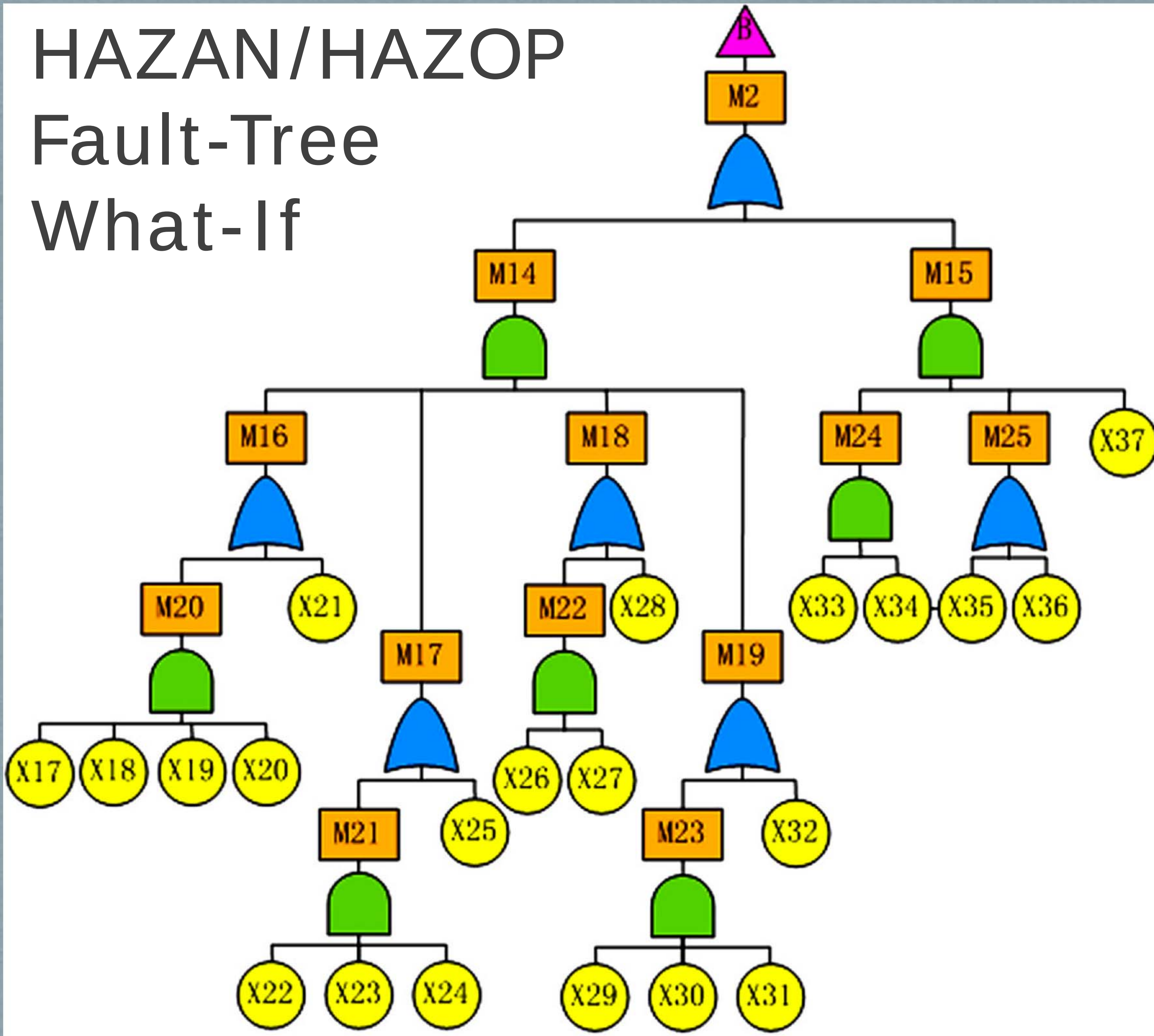
		PROBABILITY			
		Likely	Probably	May	Unlikely
		A	B	C	D
Catastrophic	SEVERITY I	1	1	2	3
Critical	II	1	2	3	4
Moderate	III	2	3	3	5
Negligible	IV	3	4	5	5

Army Risk Assessment Matrix

		PROBABILITY				
		Frequent	Likely	Occasional	Seldom	Unlikely
		A	B	C	D	E
Catastrophic	SEVERITY I	Extremely High		High		Moderate
Critical	II				Moderate	
Moderate	III	High	Moderate			
Negligible	IV	Moderate			Low	



HAZAN/HAZOP
Fault-Tree
What-If



Items for Consideration

Capture Error

a) Continuously consider “error”
b) Understand compounding error (e^x)
c) If's, averages, and assumptions
d) Describe the error and it’s implications
e) Impact of false positives vs. false negatives

- Expert Opinion Elicitation (EOE)

  - ► Solicitation of “experts” to assist in determining probabilities of unsatisfactory performance or rates of occurrence.
  - ► Need proper guidance and assistance to solicit and train the experts properly to remove all bias and dominance.
  - ► Should be documented well for ATR/IEPR
  - ► Used frequently when limit states are not easily defined and data is poor
  - ► Used commonly in Dam and Levee Safety Risk Assessments

Dam Safety Program

- Screening Portfolio Risk Assessment (2003-2007)
  - ► Examined USACE portfolio of ~620 flood control and navigation dams
  - ► Relative risk method
    - Loading ranges established for flood and seismic loads
    - Used base rate adjustment for critical failure modes
      - ▷ Base rates adjusted by four descriptors (A, PA, PI, I)
    - Consequences for load events

Engineering Rating Summary

Feature Navigation High Head Dam	Normal Water Level	50% Exceedence Duration Water Level with OBE	50% Exceedence Duration Water Level with MDE	Unusual (100yr)	Extreme (PMF)
Concrete Structures – Rock Foundation					
External Stability	I	PA	PI	I	I
Internal Stability	I	PA	PI	I	I
Foundation Stability – under dam	PA	A	A	PA	PA
Scour Protection	PA	A	A	PA	PA
Foundation -Seepage & Piping	PA	A	A	PA	PA
Abutment Foundation Stability	A	A	A	A	A
Concrete Structures – Pile Foundation					
Foundation Seepage & Piping (Incl. upstream cu	NA	NA	NA	NA	NA
Foundation Liquifaction	NA	NA	NA	NA	NA
External Stability1	NA	NA	NA	NA	NA
Foundation Stability (Incl. pile capacity) 1	NA	NA	NA	NA	NA
Internal Stability	NA	NA	NA	NA	NA
Scour Protection	NA	NA	NA	NA	NA
....................Void....................	NA	NA	NA	NA	NA
Abutment Foundation Stability1	NA	NA	NA	NA	NA
Gates & Gate Structure					
Spillway gate(s) failure 2	I	PA	PA	I	I
Spillway gate piers – structural capacity	PA	A	PA	PA	PA
Gates – Electrical/Mechanical	A	A	PA	A	PA
Lock gates (struct/elect/mech)	I	PA	PI	I	I
....................Void..............	NA	NA	NA	NA	NA
Embankment & Closure Dikes					
Embankment Seepage & Piping	PA	A	A	PA	PA
Embankment Stability and/or Liquefaction	A	A	PA	A	A
Erosion: Toe, Surface & Crest	A	A	A	A	PA
Abutments Seepage & Piping	A	A	A	A	A
Abutments Stability and/or Liquefaction	A	A	A	A	A
Foundation Seepage & Piping	A	A	A	A	A
Foundation Stability and/or Liquefaction	A	A	A	A	A
Emergency Closure Systems					
Service bridge,	A	A	PA	A	A
Crane & Power	A	A	PA	A	A
Bulkheads	PI	A	A	A	A
....................Void....................	NA	NA	NA	NA	NA
Other Features					
Feature 1	A	A	PA	A	PA
Feature 2	NA	NA	NA	NA	NA
Feature 3	NA	NA	NA	NA	NA
Feature 4	NA	NA	NA	NA	NA

Definition of Engineering Ratings

A	Adequate = 1	confidence backed up by data, studies, or obvious project characteristics and judged to meet current engineering standards and criteria.
PA	Probably Adequate = 10	and may not specifically meet criteria. Requires additional investigation or studies to confirm adequacy.
PI	Probably Inadequate = 100	confidence and requires additional studies and investigations to confirm. Judged to not meet current criteria.
I	Inadequate = 1000	confidence. Physical signs of distress are present. Analysis indicates factor of safety near limit state.
NA	Not Applicable = 0	Feature does not exist

BUILDING STRONG®

Dam Safety Program

- ER 1156 Risk Assessment Methodology
  - ► Potential Failure Mode Analysis (PFMA)
    - • Evaluate and Describe Potential Failure Modes
  - ► Construct Event Trees to Analytically Describe the Potential Path to Failure
  - ► Use Expert Elicitation with an Experienced Facilitator to Evaluate Relative Likelihoods of Each Event Tree Branch
  - ► Use the Analysis to Develop a Rational Case to Support a Decision
  - ► Examine tolerable risk curves (Farmer's Curves)

Risk Assessment Framework

P(Load) * P(Failure | Load) * Consequences = RISK

P(Load)

- Likelihood of a Loading Event
- Flood Loading or Seismic Loading

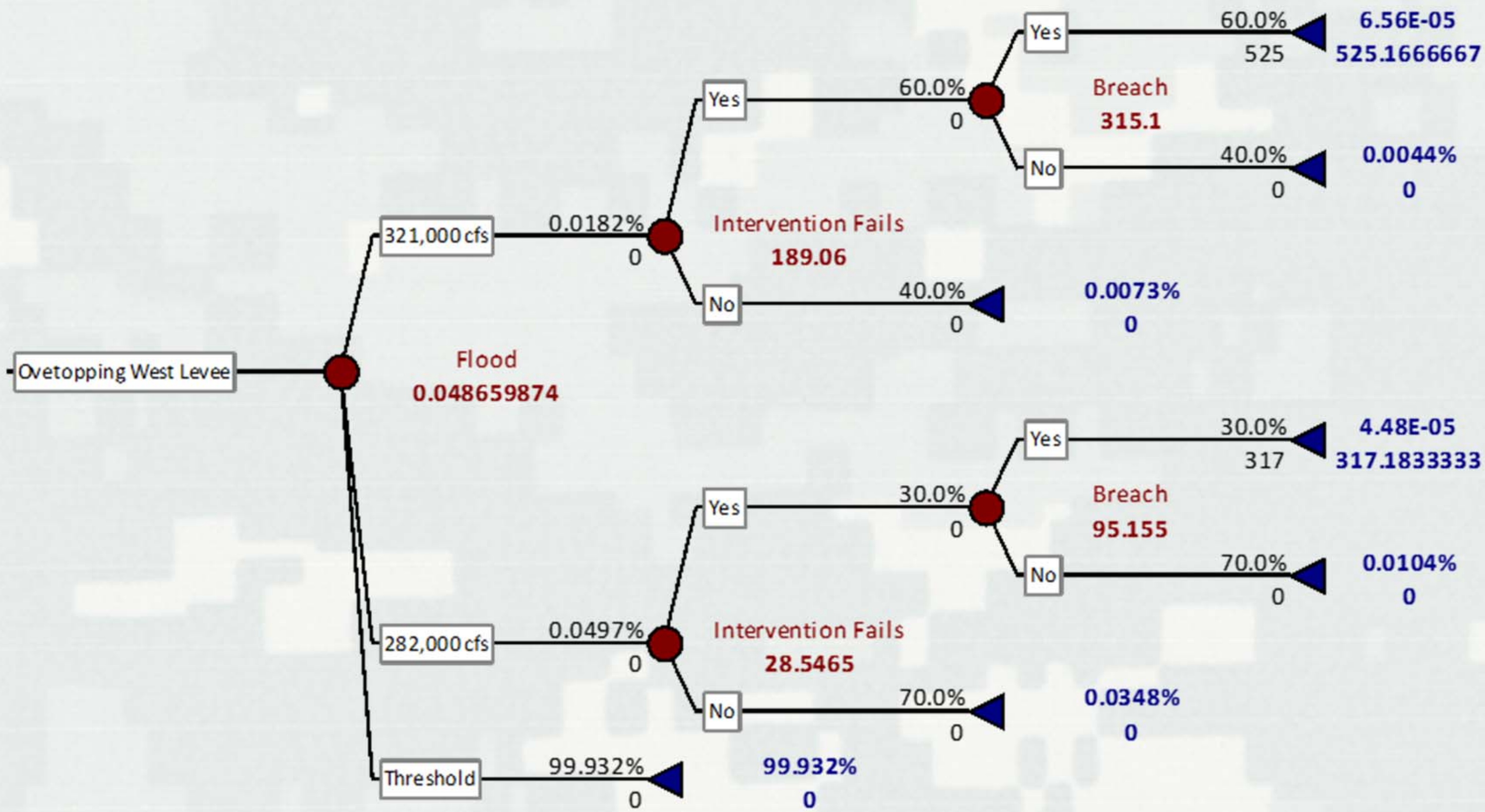
P(Failure | Load)

- Given the Event Occurs, What is the Likelihood of Adverse Structural Response of the System?
- Event Tree Construction

Consequences

- For Each Specific Adverse Response, What are the Life Safety and Economic Consequences?

Event Trees

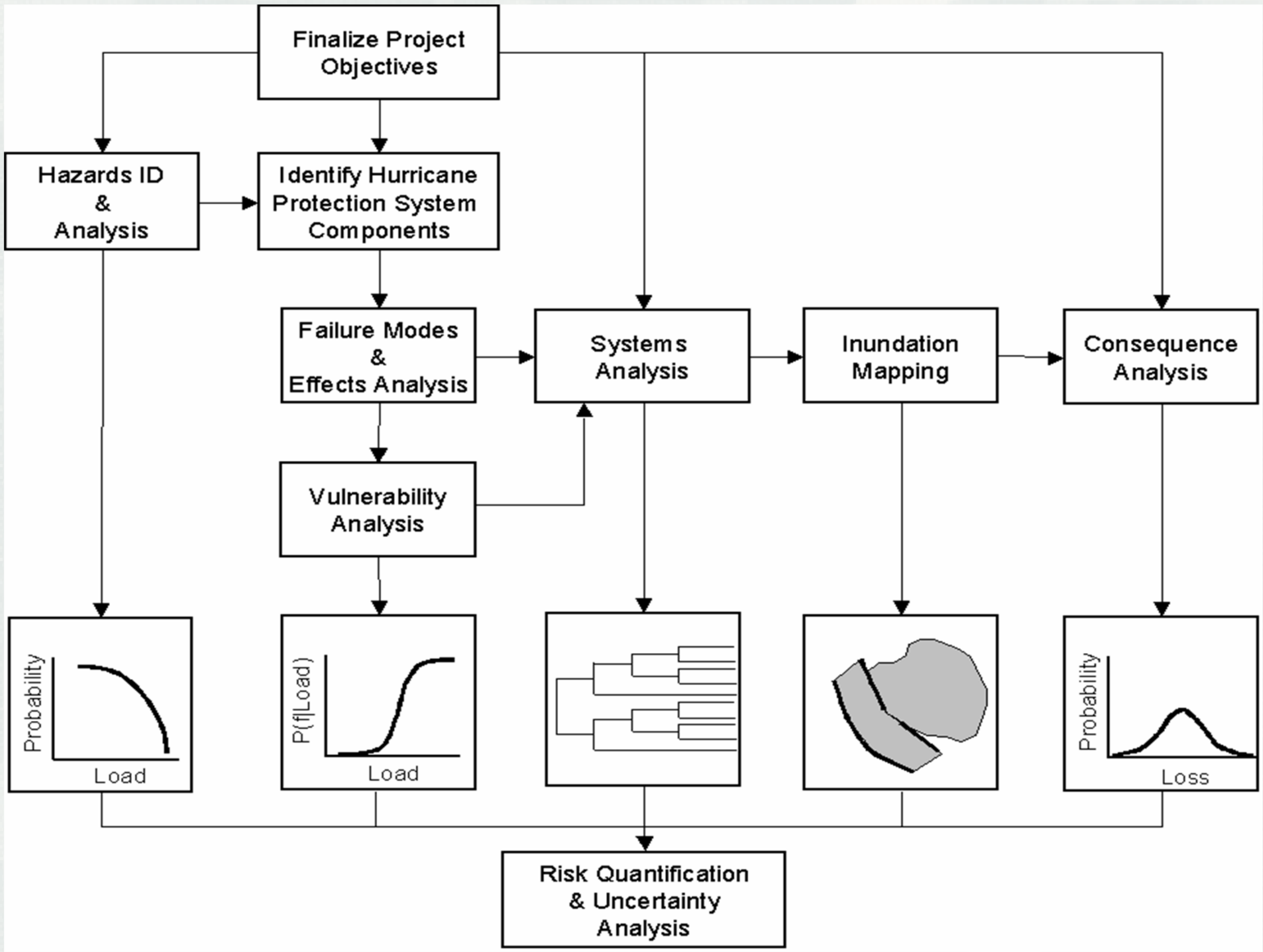


Ovetopping West Levee
Flood
0.048659874
321,000 cfs
0.0182%
0
Intervention Fails
189.06
Yes
60.0%
0
Breach
315.1
Yes
60.0%
525
6.56E-05
525.1666667
No
40.0%
0
0.0044%
0
No
40.0%
0
0.0073%
0
282,000 cfs
0.0497%
0
Intervention Fails
28.5465
Yes
30.0%
0
Breach
95.155
Yes
30.0%
317
4.48E-05
317.1833333
No
70.0%
0
0.0104%
0
No
70.0%
0
0.0348%
0
Threshold
99.932%
0
99.932%
0

Dam Safety Program

- Semi-Quantitative Risk Assessment (SQRA)
  - ►Screening level approach but more rigor than SPRA
  - ►Risk matrix approach to examining probability of failures and consequences
  - ►Uses PFMA to estimate probability of failure
  - ►Uses rough estimates for consequences (loss of life and direct economic loss)

Risk Assessment



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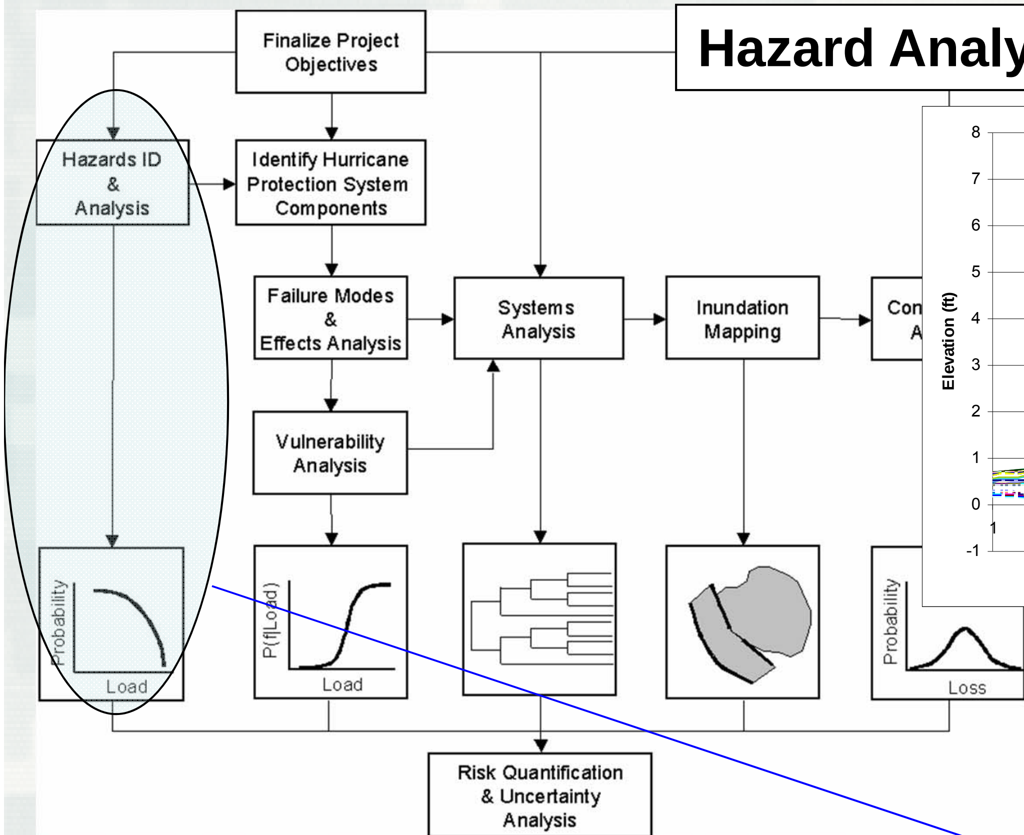
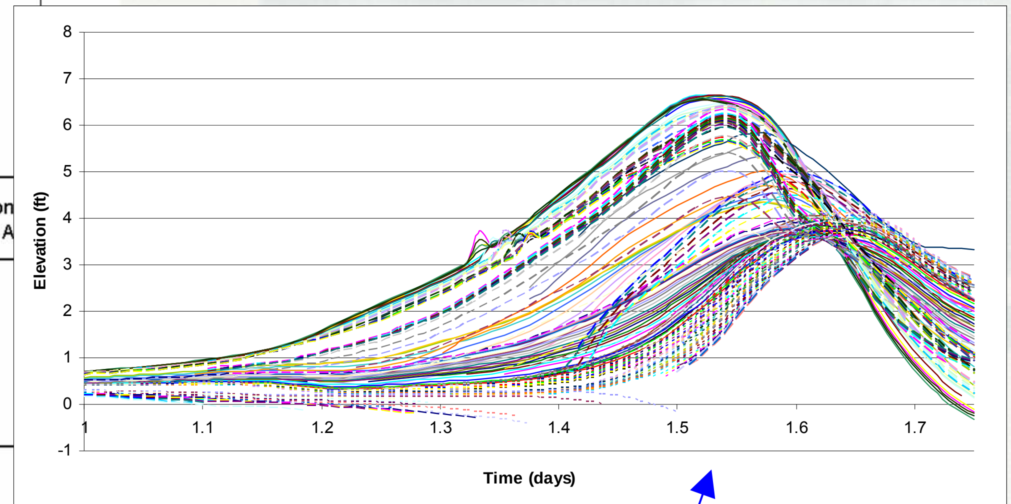
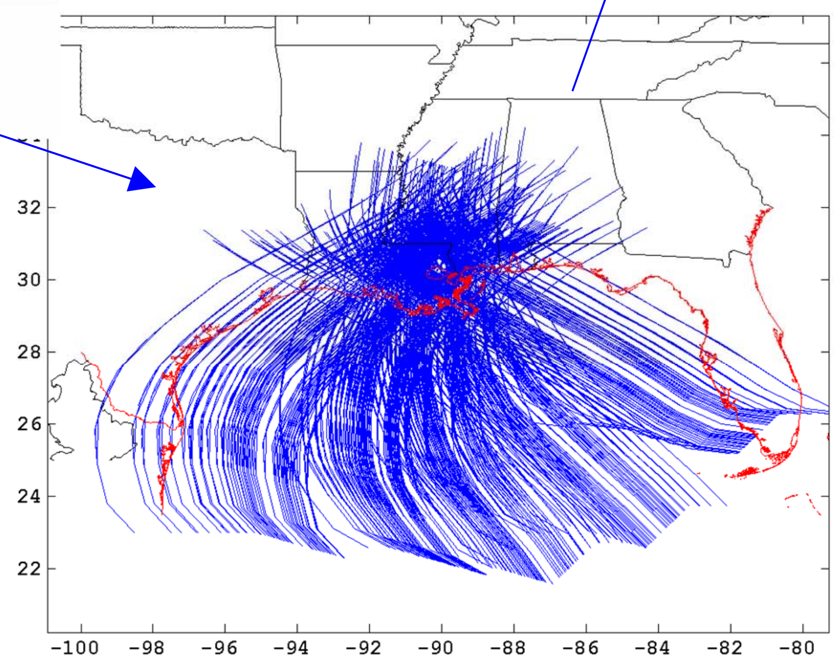
Hazard Analysis



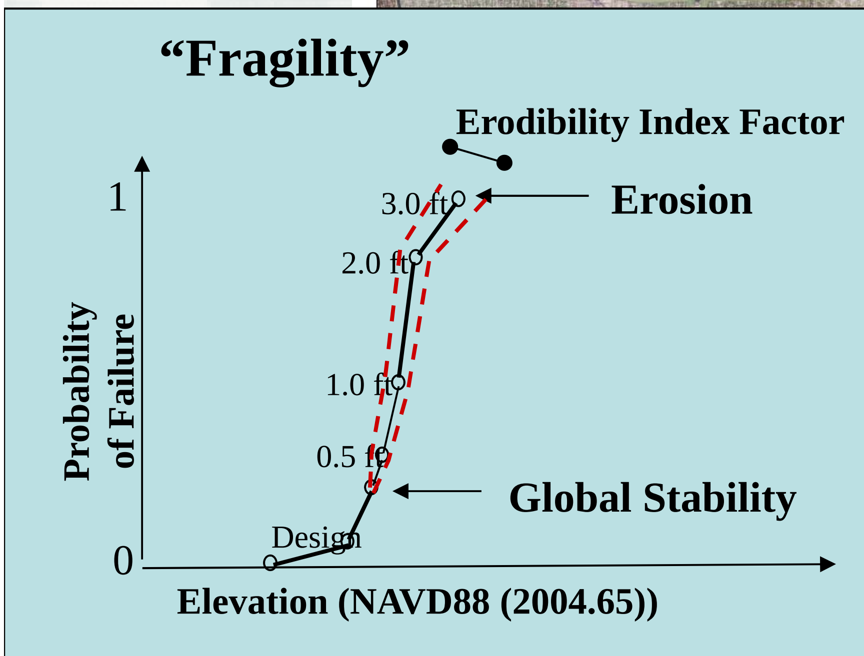




Storm Modeling

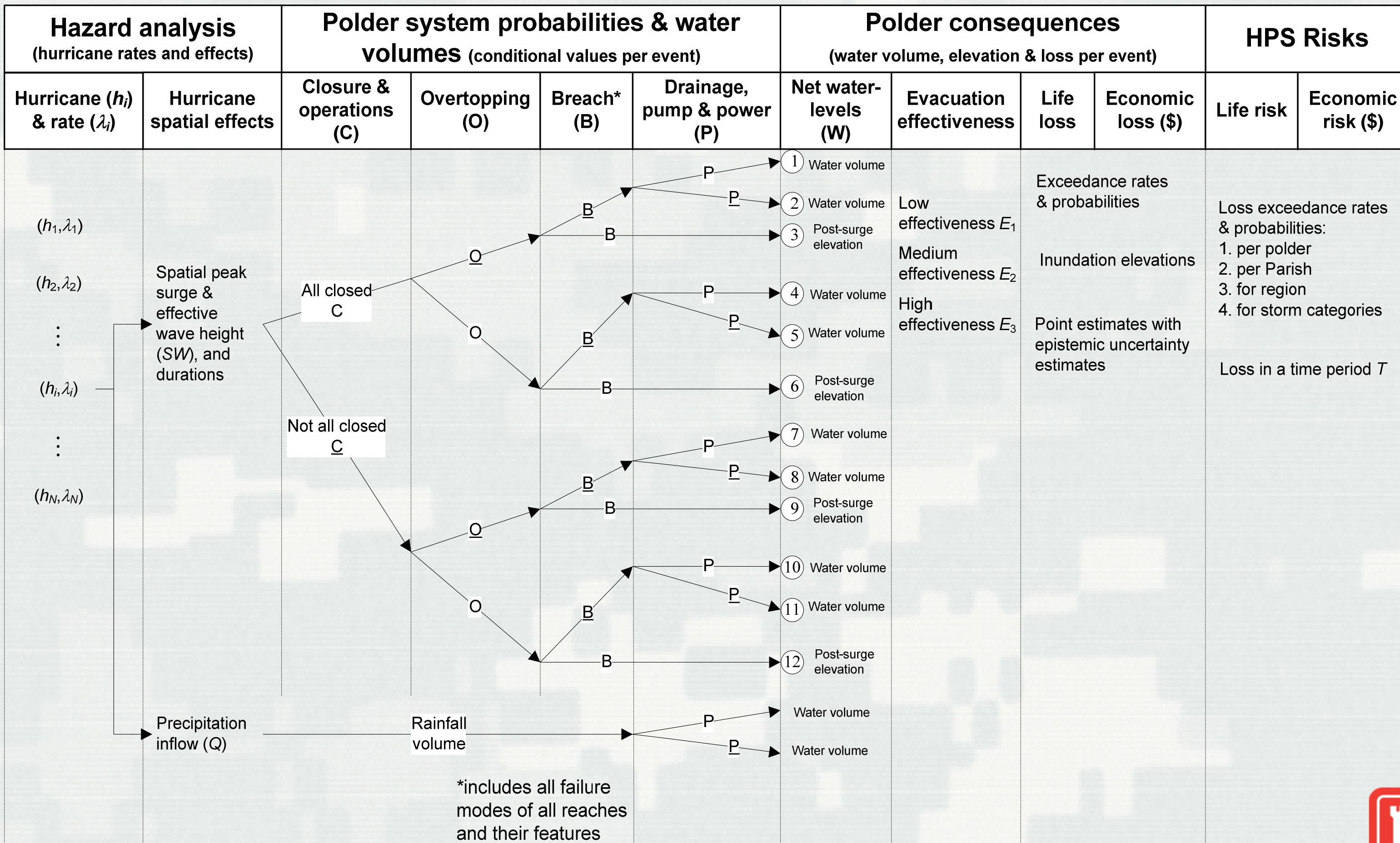
- ADCIRC
- Historic storms in parameter set
- 100± Low Res Runs
- 1800± Med Res Runs
- 60± High Res Runs
- Frequency Analysis
- ~~Calibrate (HWM & Storm Team Results~~)
- Add Waves

System Performance



Elevations consider expected sea level rise, subsidence and settlement

Event Tree

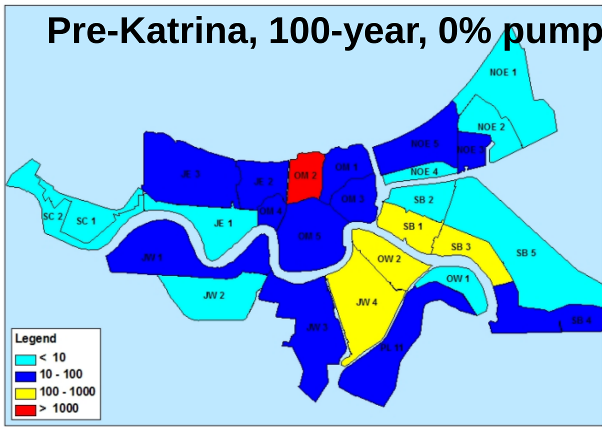


Hazard analysis
(hurricane rates and effects)
Polder system probabilities & water volumes (conditional values per event)
Polder consequences
(water volume, elevation & loss per event)
HPS Risks
Hurricane (h_i) & rate (λ_i)
Hurricane spatial effects
Closure & operations (C)
Overtopping (O)
Breach* (B)
Drainage, pump & power (P)
Net water-levels (W)
Evacuation effectiveness
Life loss
Economic loss ($)
Life risk
Economic risk ($)
(h_1,λ_1)
(h_2,λ_2)
(h_i,λ_i)
(h_N,λ_N)
Spatial peak surge & effective wave height (SW), and durations
Precipitation inflow (Q)
All closed C
Not all closed C
O
B
P
Rainfall volume
1 Water volume
2 Water volume
3 Post-surge elevation
4 Water volume
5 Water volume
6 Post-surge elevation
7 Water volume
8 Water volume
9 Post-surge elevation
10 Water volume
11 Water volume
12 Post-surge elevation
Water volume
Water volume
Low effectiveness E_1
Medium effectiveness E_2
High effectiveness E_3
Exceedance rates & probabilities
Inundation elevations
Point estimates with epistemic uncertainty estimates
Loss exceedance rates & probabilities:
1. per polder
2. per Parish
3. for region
4. for storm categories
Loss in a time period T
*includes all failure modes of all reaches and their features

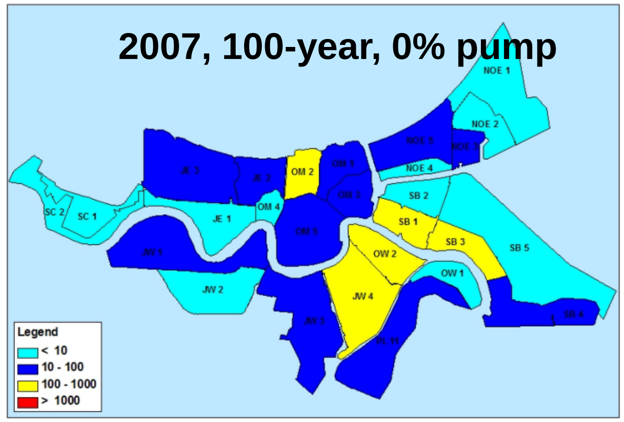
Loss of Life Risk Maps

(Pre-K Population and Property)

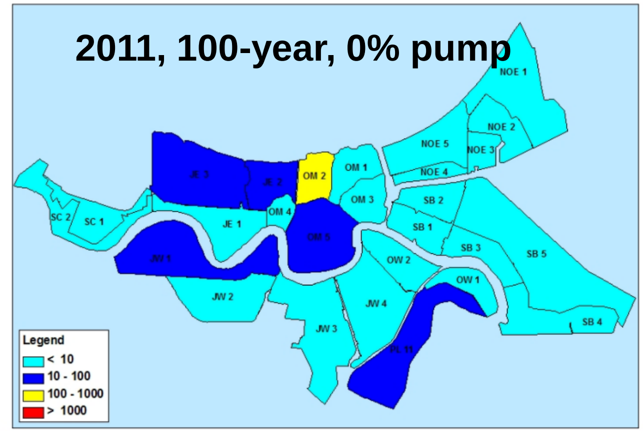
Hurricane Protection System in place before Katrina with no pumping
There was a 1% (1 in 100) chance for this number of fatalities



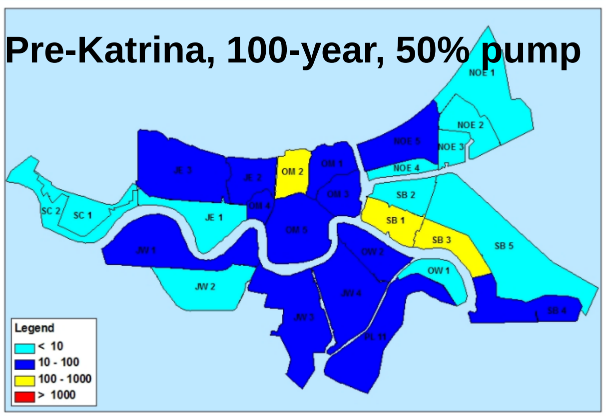
Hurricane Protection System in place in June 2007 with no pumping
There was a 1% (1 in 100) chance for this number of fatalities



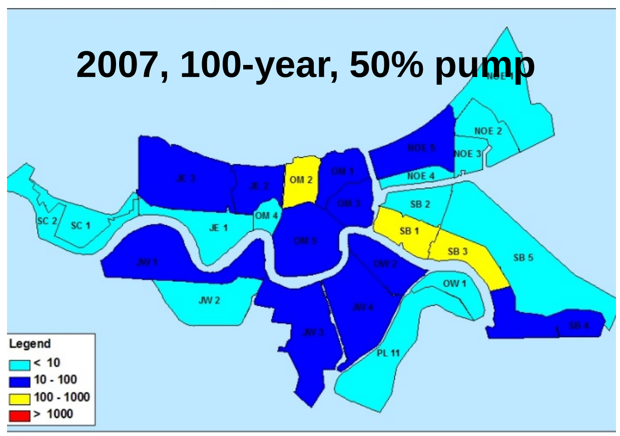
100-Year Hurricane Protection System with no pumping
There is a 1% (1 in 100) chance for this number of fatalities



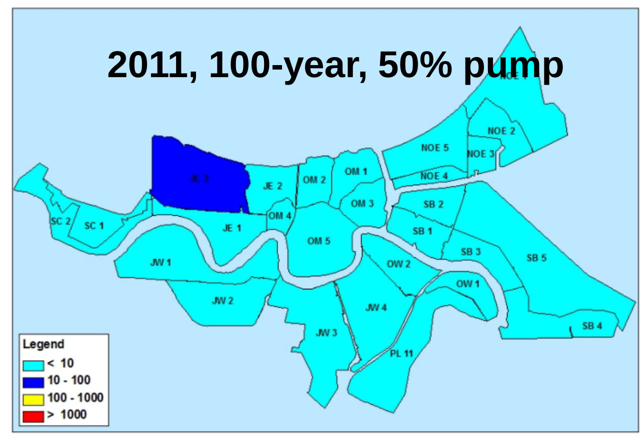
Hurricane Protection System in place before Katrina with pumping at 50% of capacity
There was a 1% (1 in 100) chance for this number of fatalities



Hurricane Protection System in place in June 2007 with pumping at 50% of capacity
There was a 1% (1 in 100) chance for this number of fatalities



100-Year Hurricane Protection System with pumping at 50% of capacity
There is a 1% (1 in 100) chance for this number of fatalities



Levee Safety Program

- Current Risk Assessment Methodology
  - ► Potential Failure Mode Analysis (PFMA)
    - Evaluate and Describe Potential Failure Modes
  - ► Construct Event Trees to Analytically Describe the Potential Path to Failure
  - ► Use Expert Elicitation with an Experienced Facilitator to Evaluate Relative Likelihoods of Each Event Tree Branch
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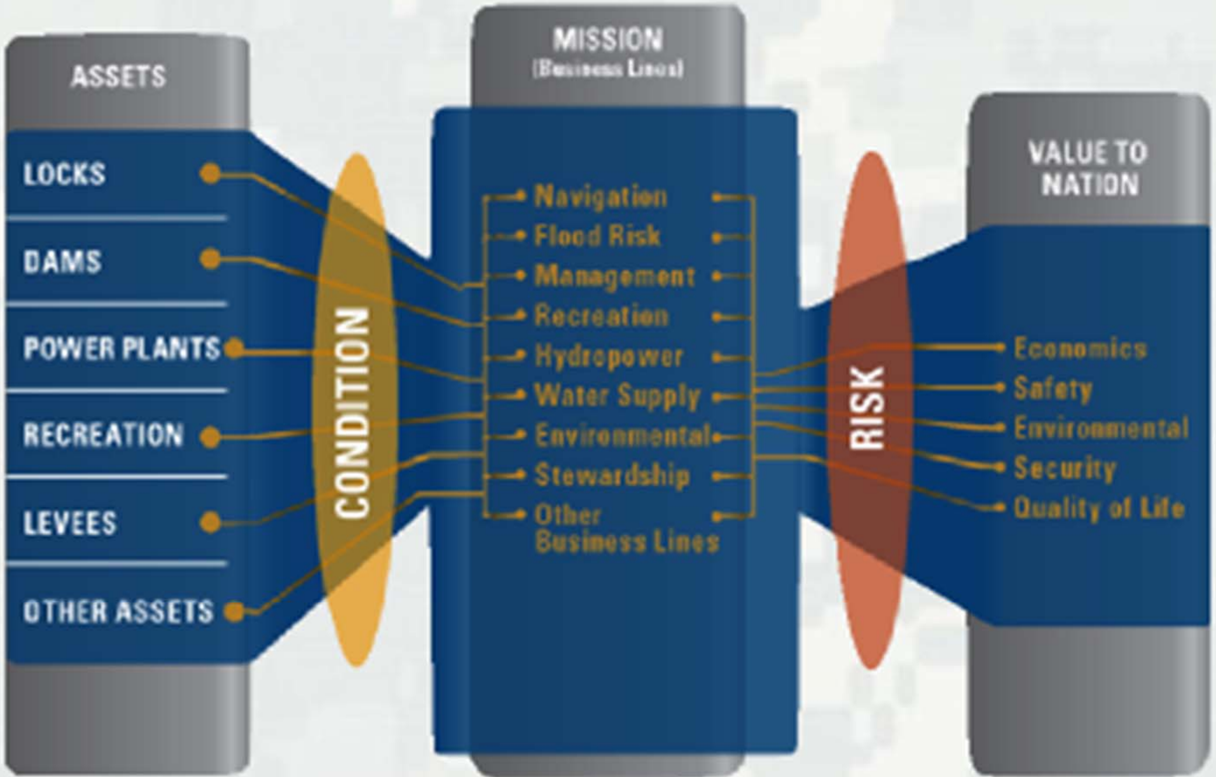
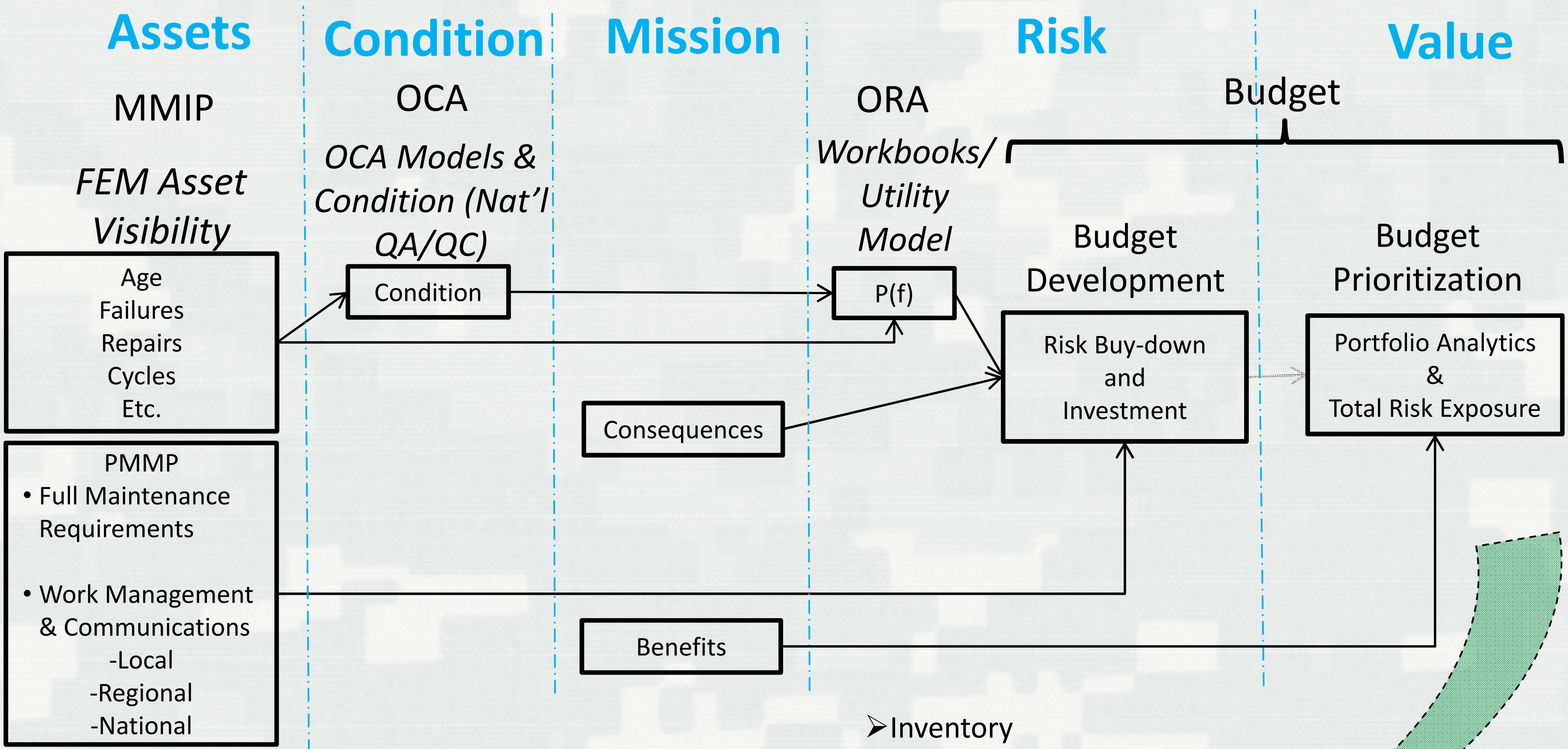
USACE Asset Management



What, where and when do I invest? Providing "Line of Sight" to enable the assets greatest Value to the Nation!

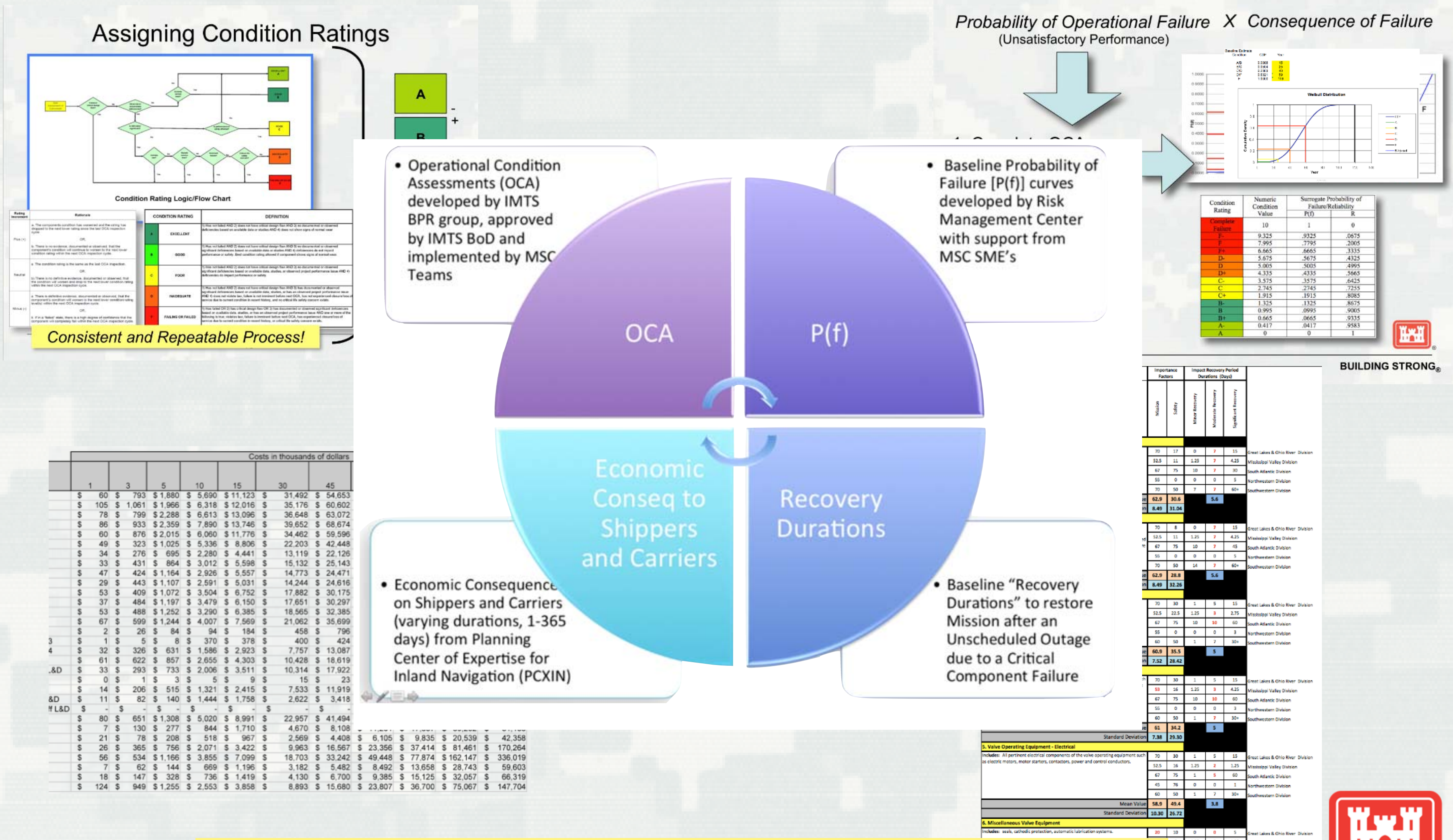
Lifecycle Portfolio Management Process



6 information elements required for effective Lifecycle Portfolio Management:

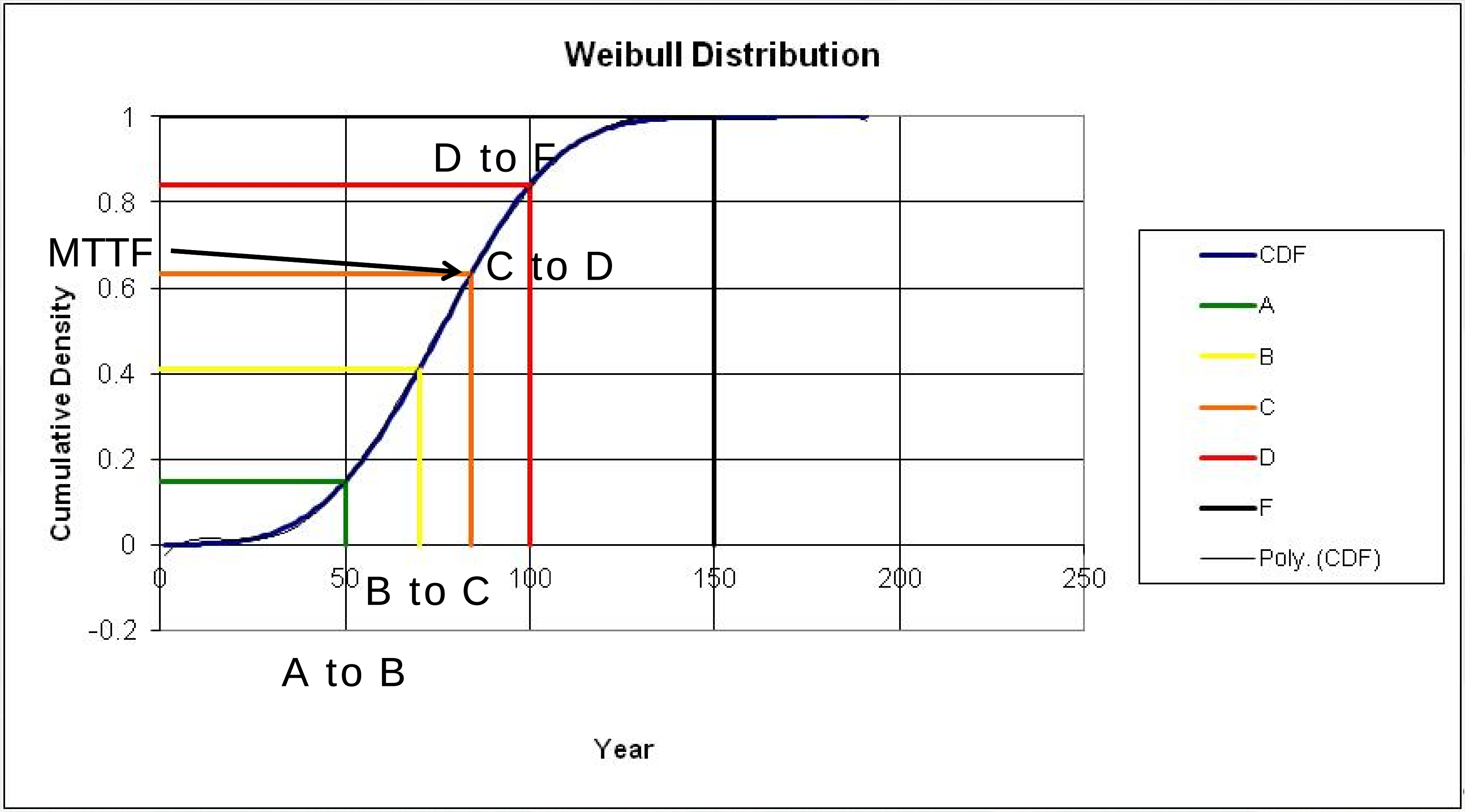
- ➢Inventory
- ➢Condition
- ➢Consequences
- ➢Requirements
- ➢Prioritization
- ➢Execution

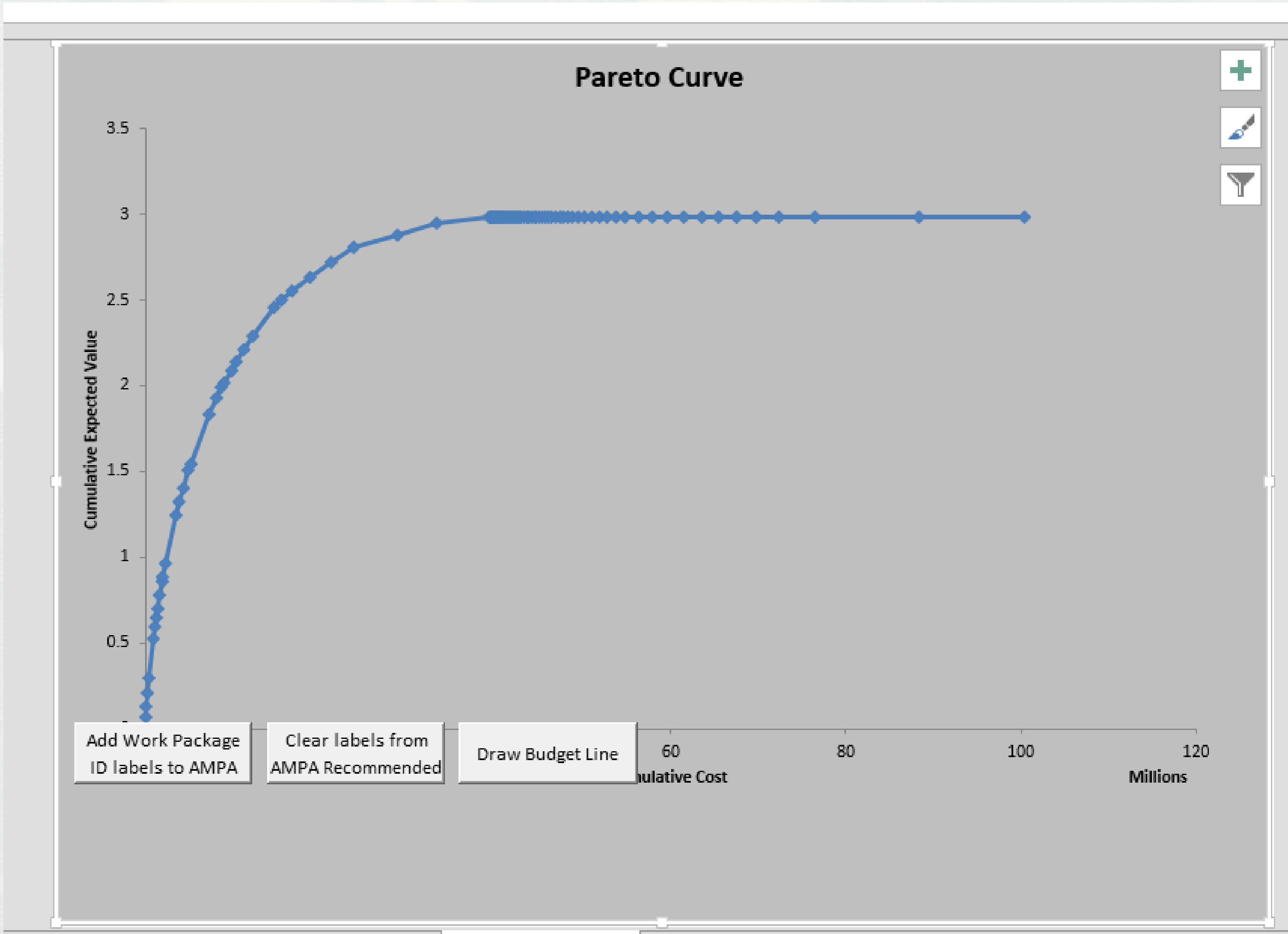
The Pieces of the Puzzle



All of this for 166,000 asset components across the IMTS!!

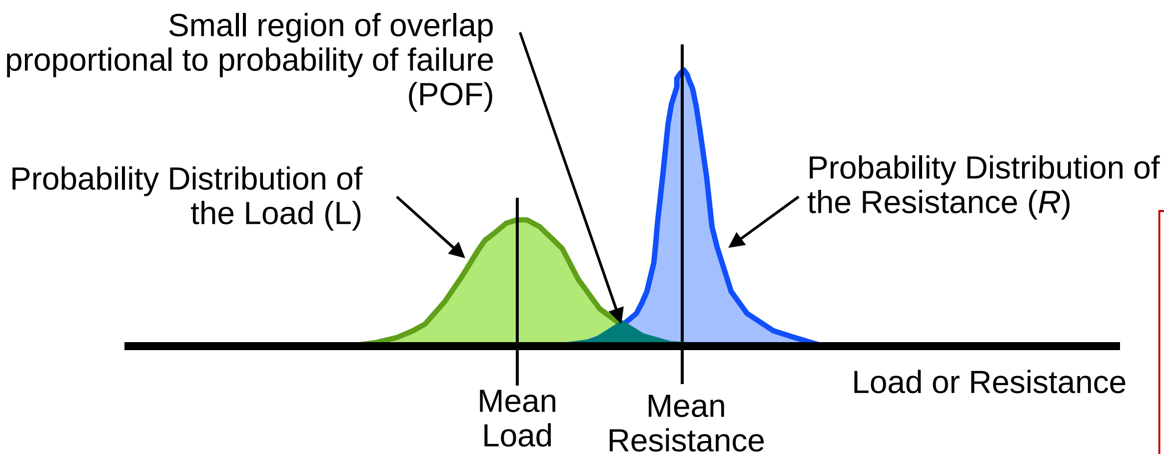
Expert-Opinion Elicitation




Pareto Curve
Cumulative Expected Value
3.5
3
2.5
2
1.5
1
0.5
60
80
100
120
ulative Cost
Millions
Add Work Package ID labels to AMPA
Clear labels from AMPA Recommended
Draw Budget Line

Model-Based Methods

- Approach
  - Develop failure prediction models that define the sets of conditions that can lead to failure → necessarily threat-specific
  - Use structural reliability methods where appropriate to combine deterministic models with input uncertainties to estimate probability (or frequency) of failure for individual threats



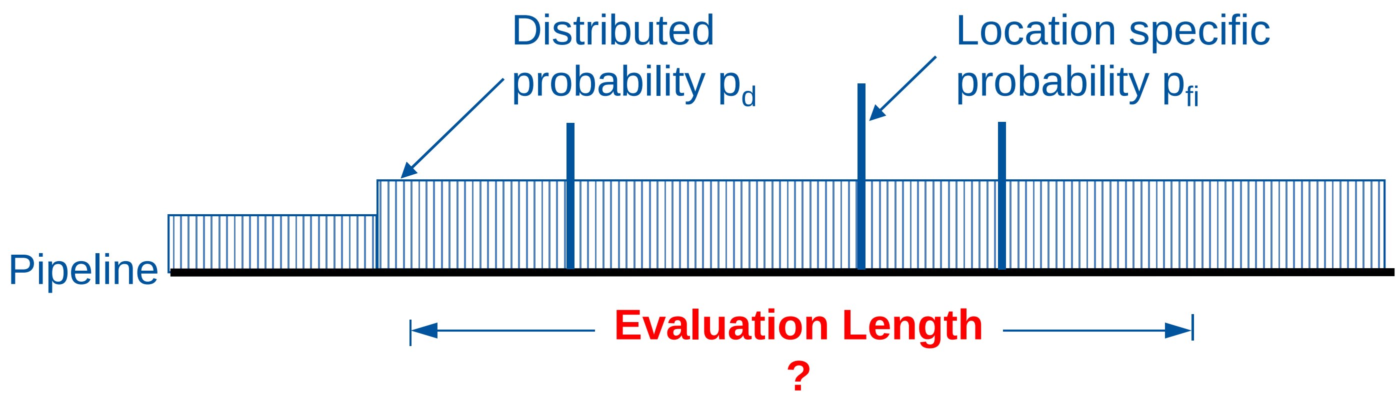
POF = P(R < L)

Central to the methodology is a formal characterization of the uncertainties inherent in both the applied load and the available resistance for each damage/deterioration mechanism (i.e. each threat)

Failure Measures

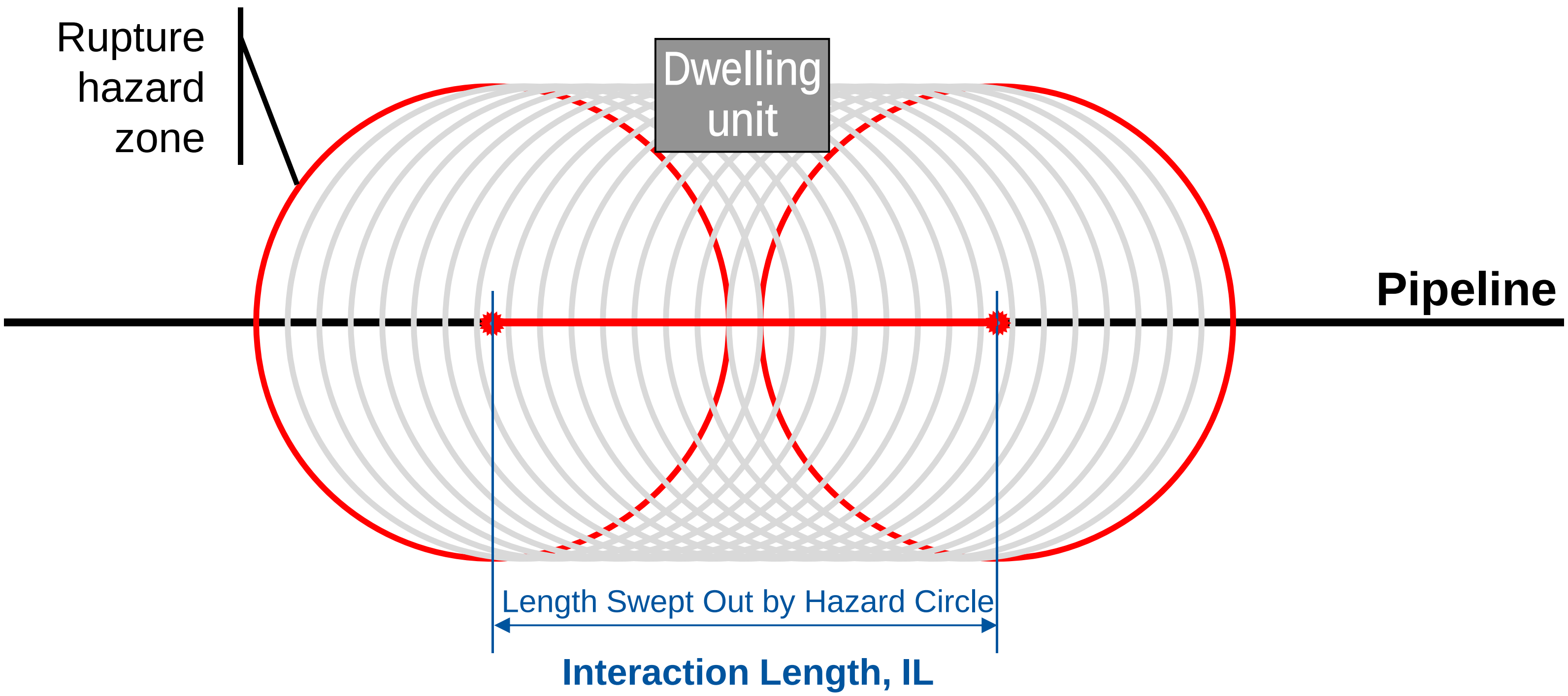
Linear system considerations

- Some integrity threats are concentrated at explicit locations
  - Locations know (e.g. corrosion defects found during inspection)
  - Best evaluated as discrete, location-specific probability
- Some integrity threats are distributed along pipeline length
  - Locations not known (e.g. future mechanical damage, corrosion defects not found)
  - Best evaluated as failure rate or distributed probability



Evaluation Length Considerations

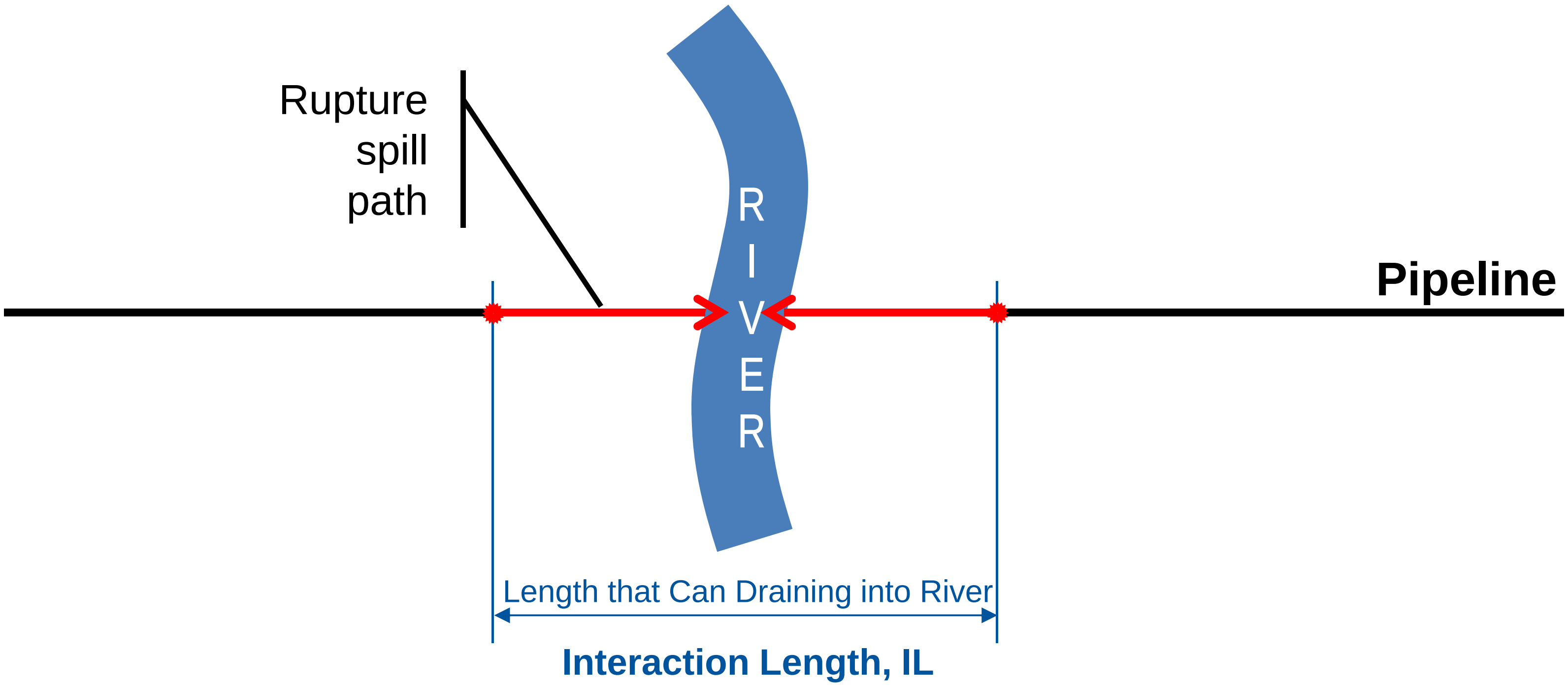
- Example: safety implications of natural gas pipeline



Interaction Length is segment length with potential to affect dwelling occupants
- occupants level of safety depends on reliability of entire IL
- level of safety depends on aggregated reliability of all defects within IL

Evaluation Length Considerations

- Example: environmental implications of LVP pipeline

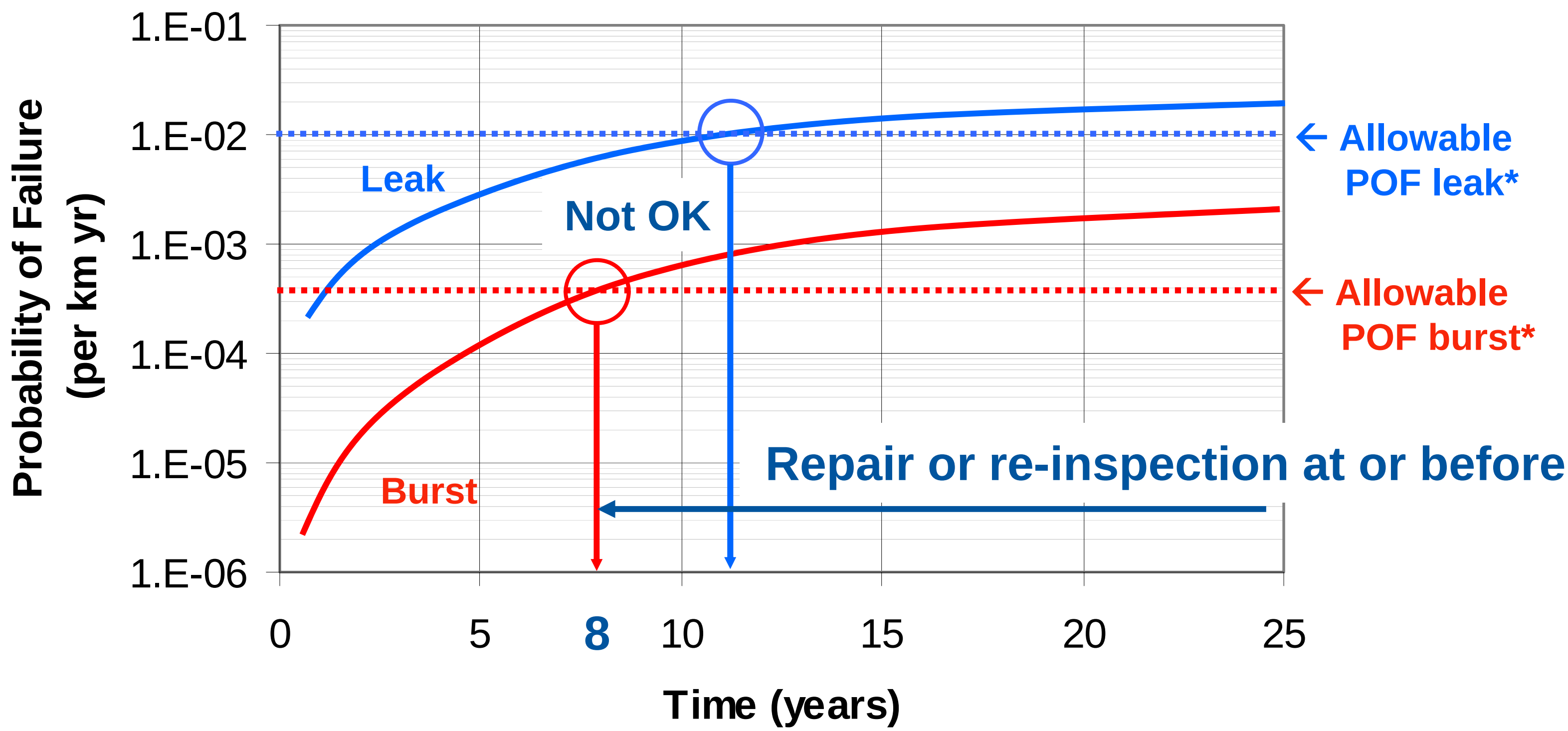


Interaction Length is segment length with potential to impact river
- level of environmental protection depends on reliability of entire IL
- level of protection depends on aggregated reliability of all defects within IL

C-FER Technologies

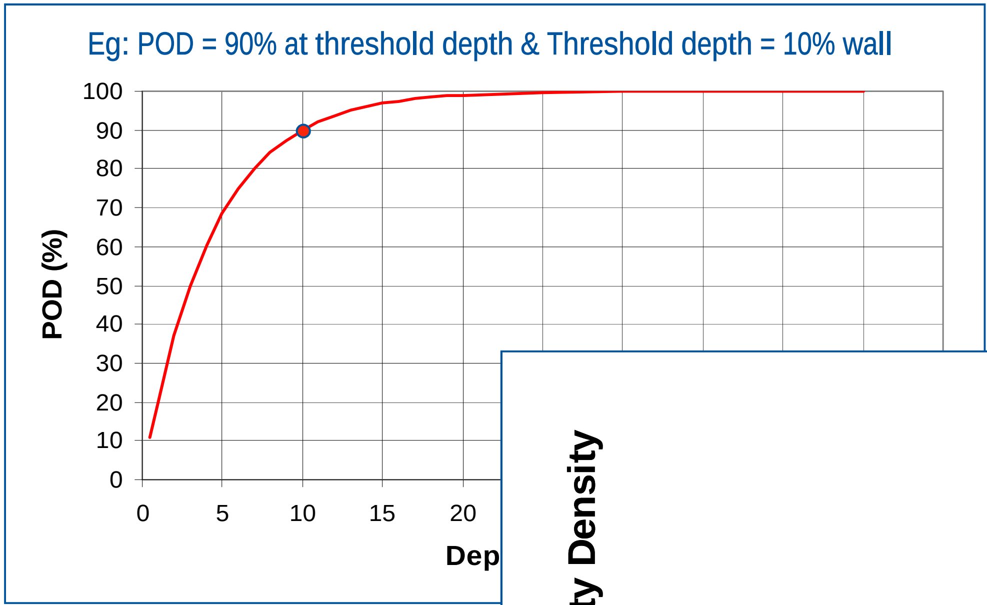
Probability Estimation

Segment reliability versus time – for given evaluation length



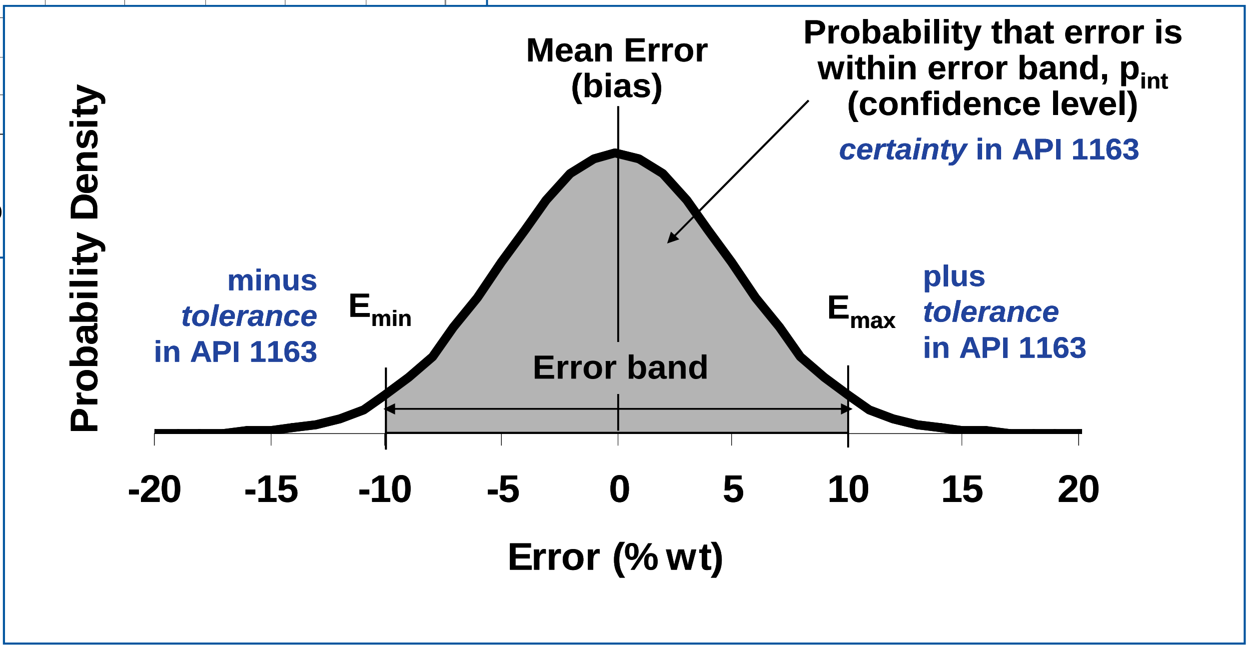
**based on risk considerations considering failure consequences*

Inspection Uncertainties – ILI Example



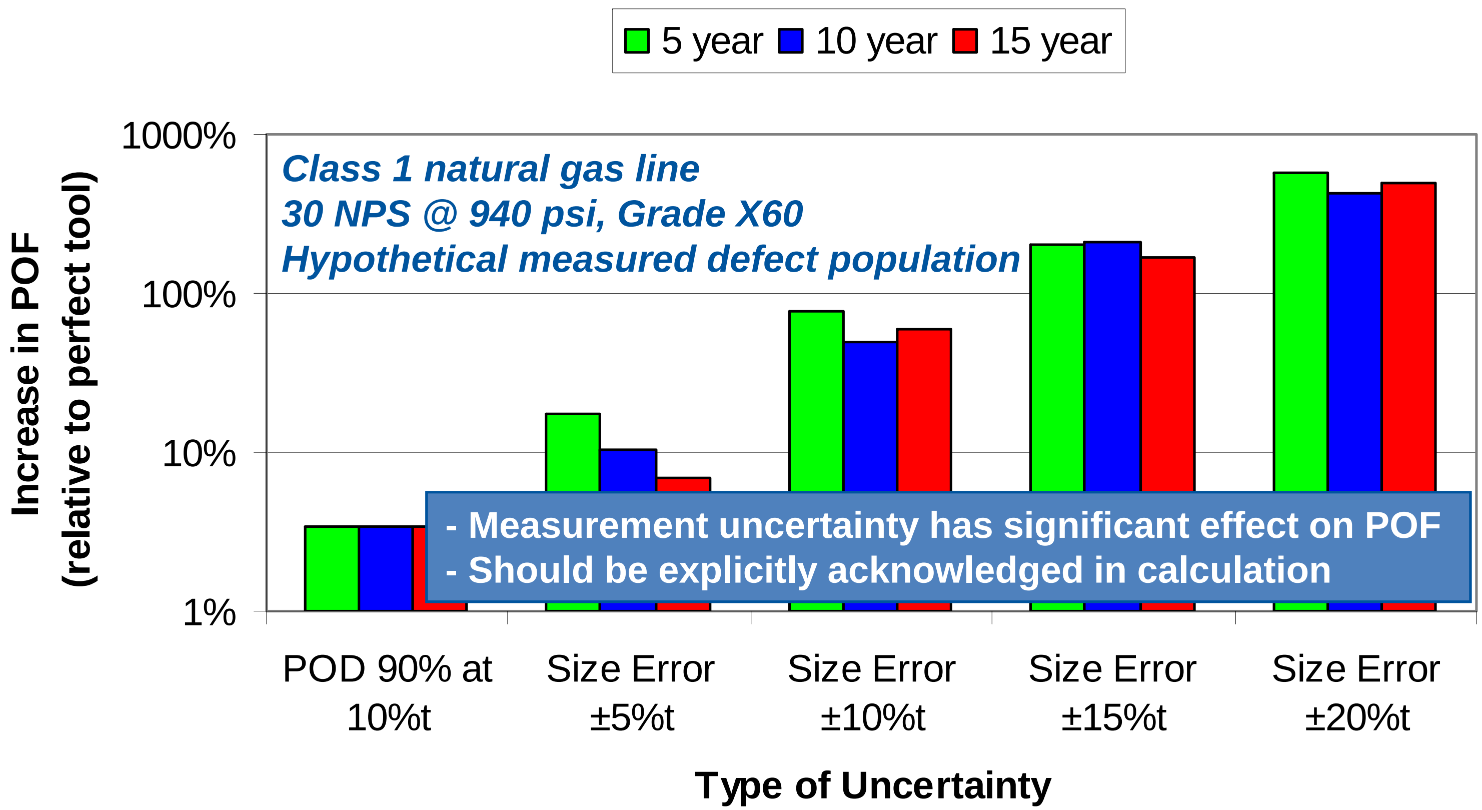
POD - Basis for inferring density & size distribution of non-detected features

Tool tolerance & Confidence Interval – basis for measurement error distribution



Inspection Uncertainty – Effect on Probability of Failure

Example – Corrosion failure probability as affected by ILI uncertainty*

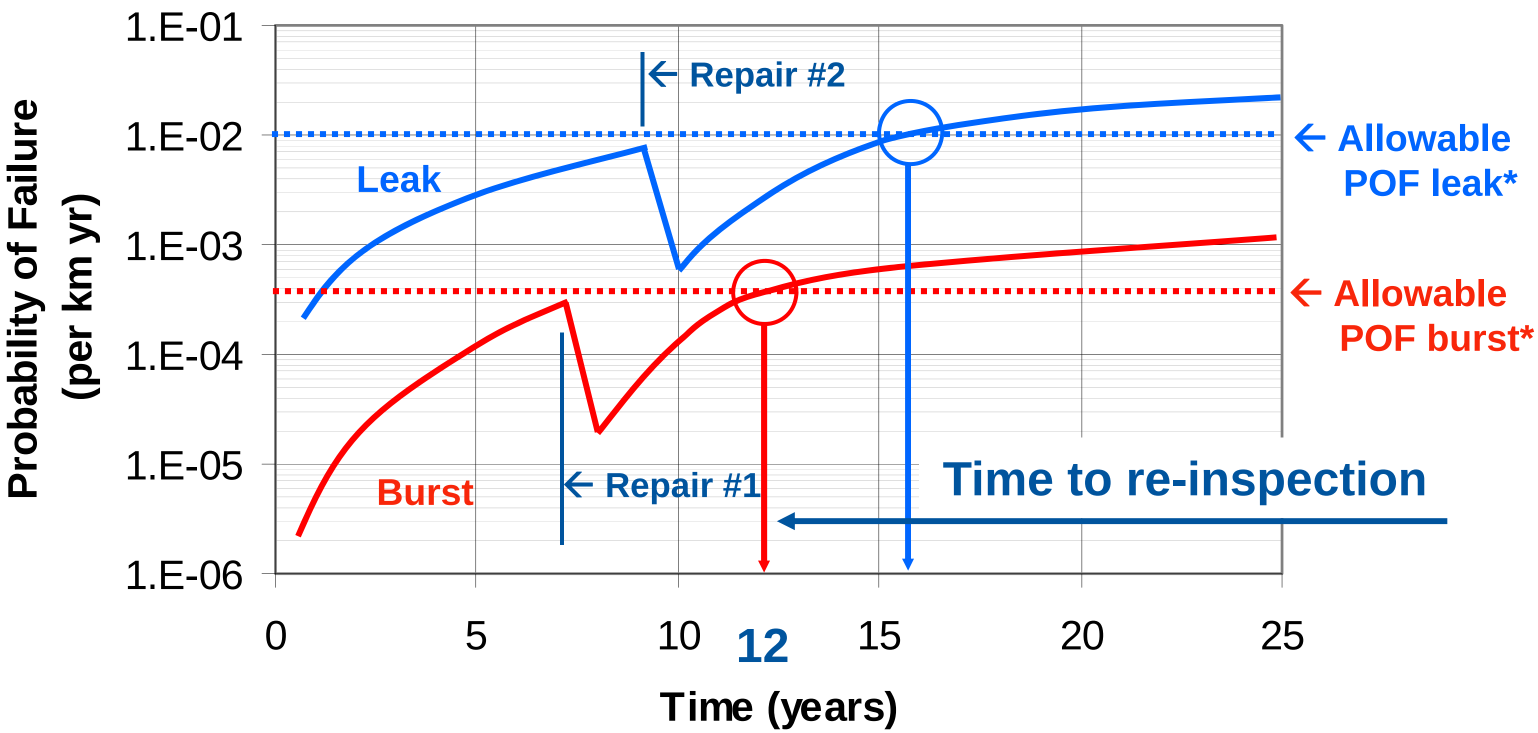


**Growth rate independent of measured defect size*

C-FER Technologies

Impact of Maintenance

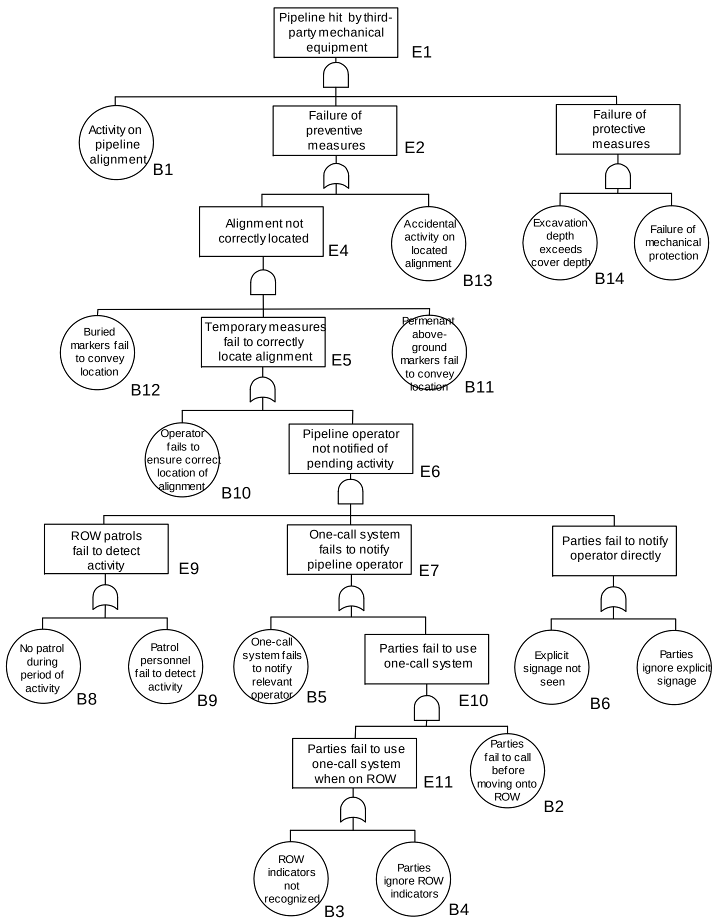
Segment reliability versus time – for given evaluation length



**based on risk considerations considering consequences*

Hit Frequency Estimation

Actual fault tree model

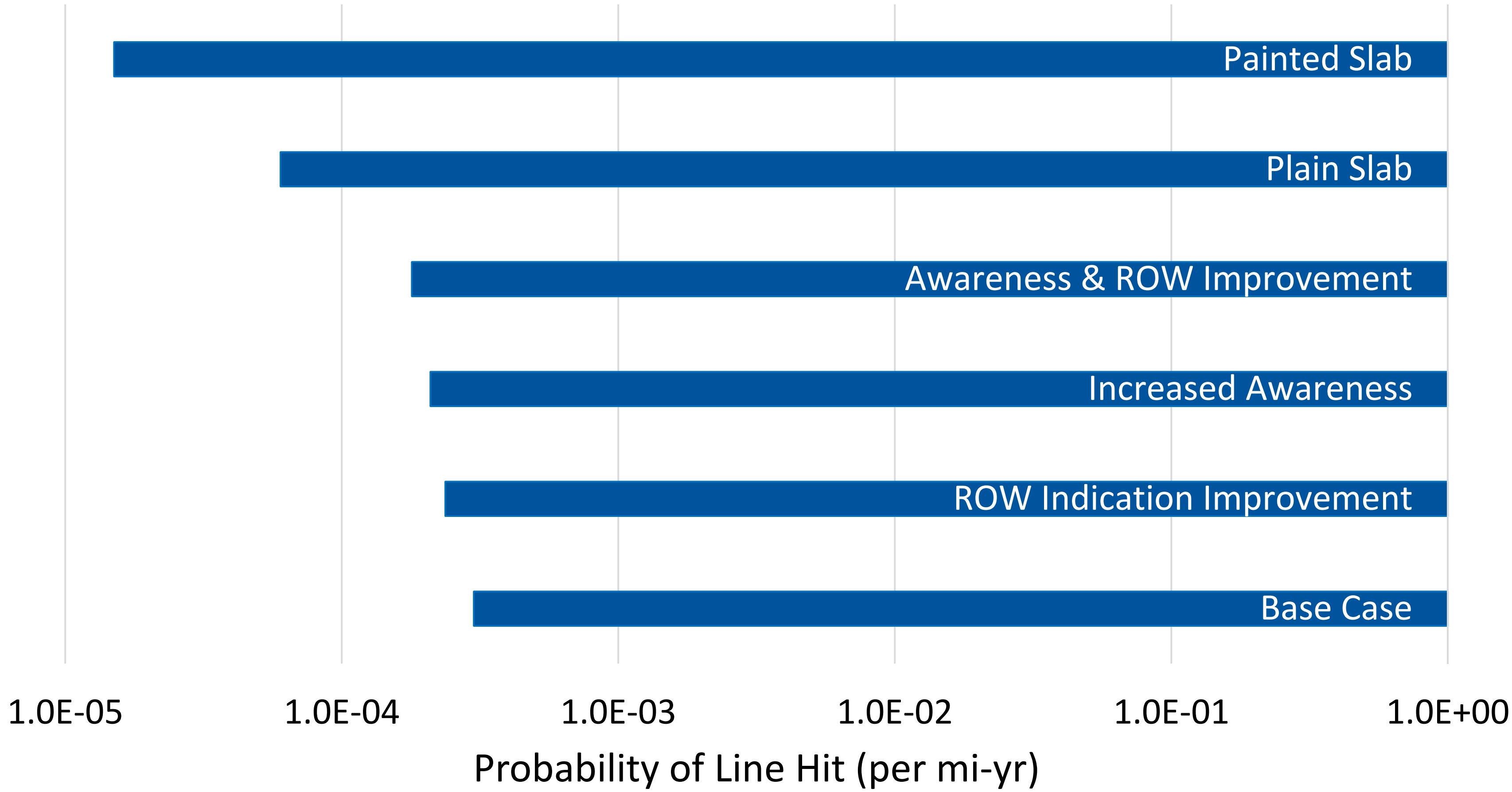


Can reflect hit frequency impact associated with wide range of system attributes and damage prevention measures

Detailed fault tree considerations

- land use & presence of crossings
- depth of burial
- one call system type
- dig notification requirement
- dig notification response
- public awareness level
- right-of-way indication
- alignment markers - explicit signage
- alignment markers - above ground
- alignment markers - buried
- surveillance method / interval
- mechanical protection

Effect of Damage Management



What does Bayesian analysis do?

- It shows us how to incorporate newly acquired evidence into our current state of knowledge regarding some parameter. Examples:
  - What does recent operating experience tell us about the failure rates of components in our system?
    - We thought the compressor failure rate was λ, but based on that, we should have had only n failures; and instead we've had $m>n$ failures.
  - What do recent test results tell us about the parameters of physical models, or even the applicability of those models to our situation?

Bayes' Theorem:

- Bayes' "theorem" states that

What we think now

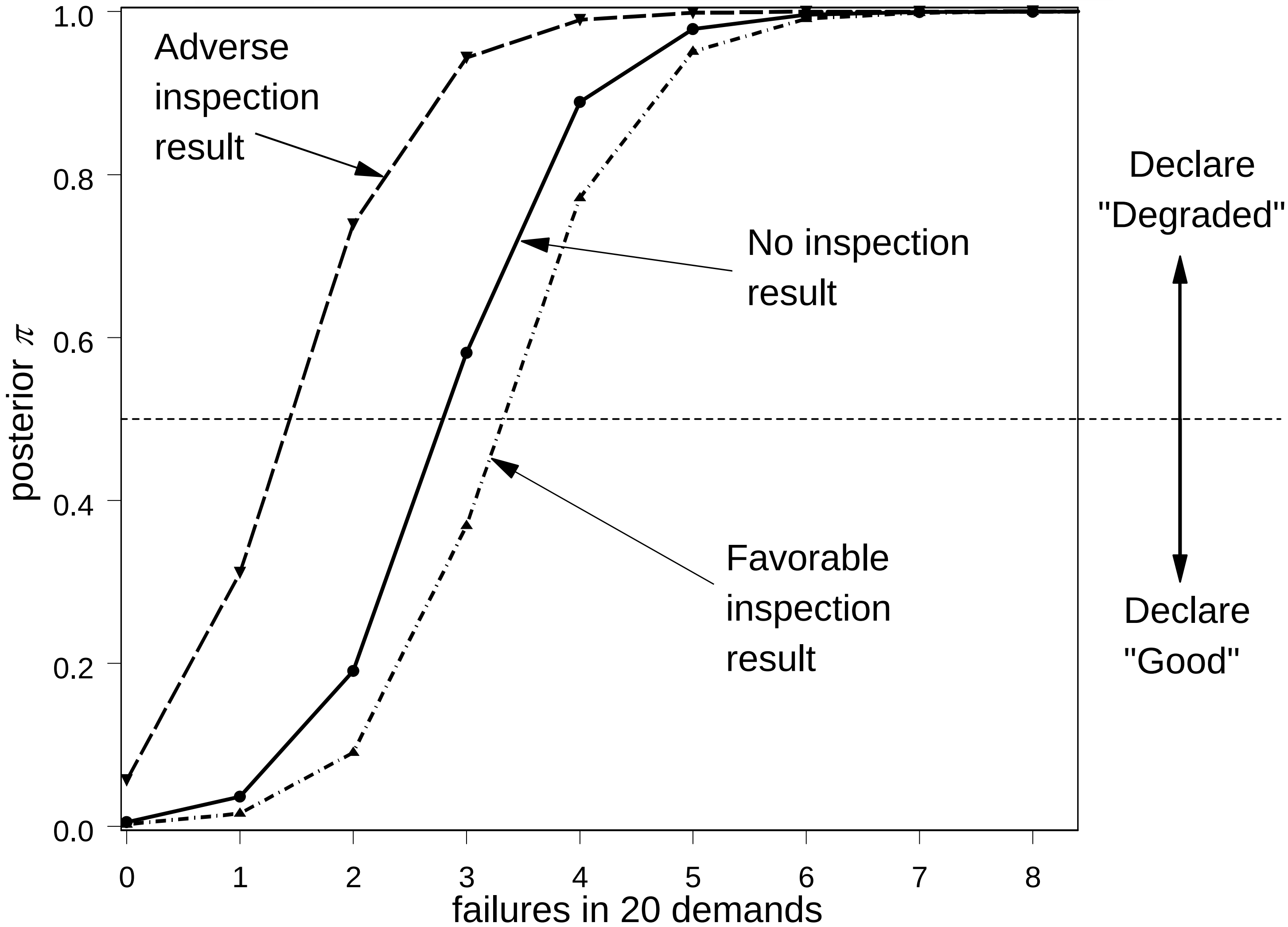
What we used to think

Factor measuring the consistency of the observed evidence E with the various competing hypotheses H_i

$$p\left(H_i \mid E\right) = P\left(H_i\right)\frac{p(E \mid H_i)}{p(E)},$$

$$p(E) = \sum_i p(E \mid H_i)\,p(H_i)$$

- where
  - H_i represents a hypothesis whose probability is to be updated with new evidence,
  - $p(H_i)$ is the prior probability of H_i,
  - E represents a new piece of evidence,
  - p(x|y) is the conditional probability of x given y,
  - p(E), the prior probability of the observed evidence


Adverse
inspection
result
No inspection
result
Favorable
inspection
result
Declare
"Degraded"
Declare
"Good"
posterior π
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
failures in 20 demands

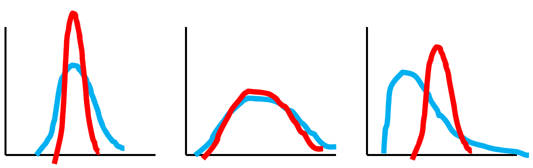
Formalism works for all kinds of things…

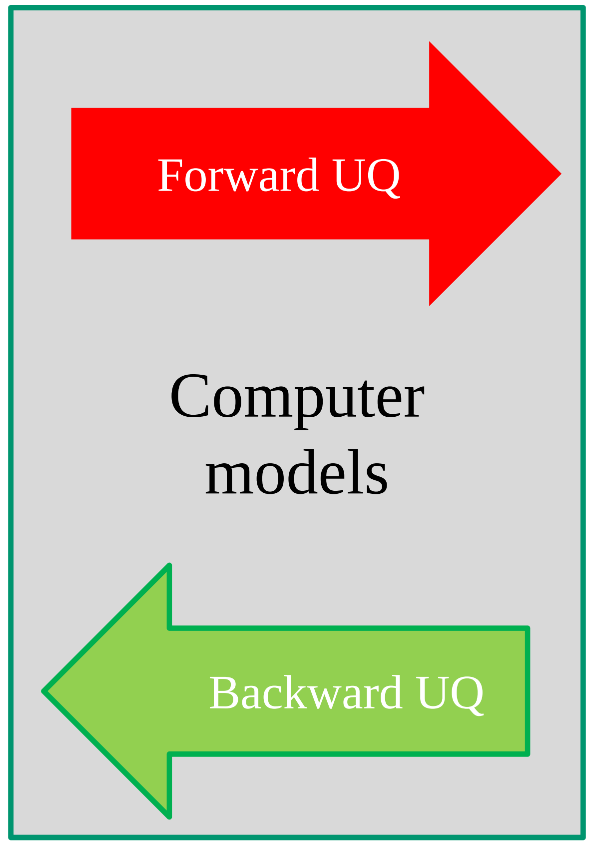
- Examples so far have stressed applications to reliability (failure rate, failure probability) based on evidence from operating experience (or "inspection")
- But the Bayesian formalism works for all kinds of things …
  - Subject of course to the caveats previously mentioned
- … Such as parameters in physics models …
  - …Even complicated ones
  - …Even many-parameter ones
  - …Even hard-to-execute models, if you use Markov Chain Monte Carlo and model emulators

Forward vs. Backward Uncertainty Quantification (UQ)

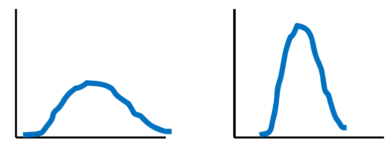
Given the input distributions, what's the uncertainty in the prediction?

Input values of uncertain parameters, initial conditions, boundary conditions, etc…



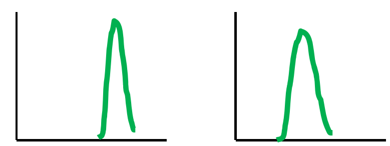


Output metrics



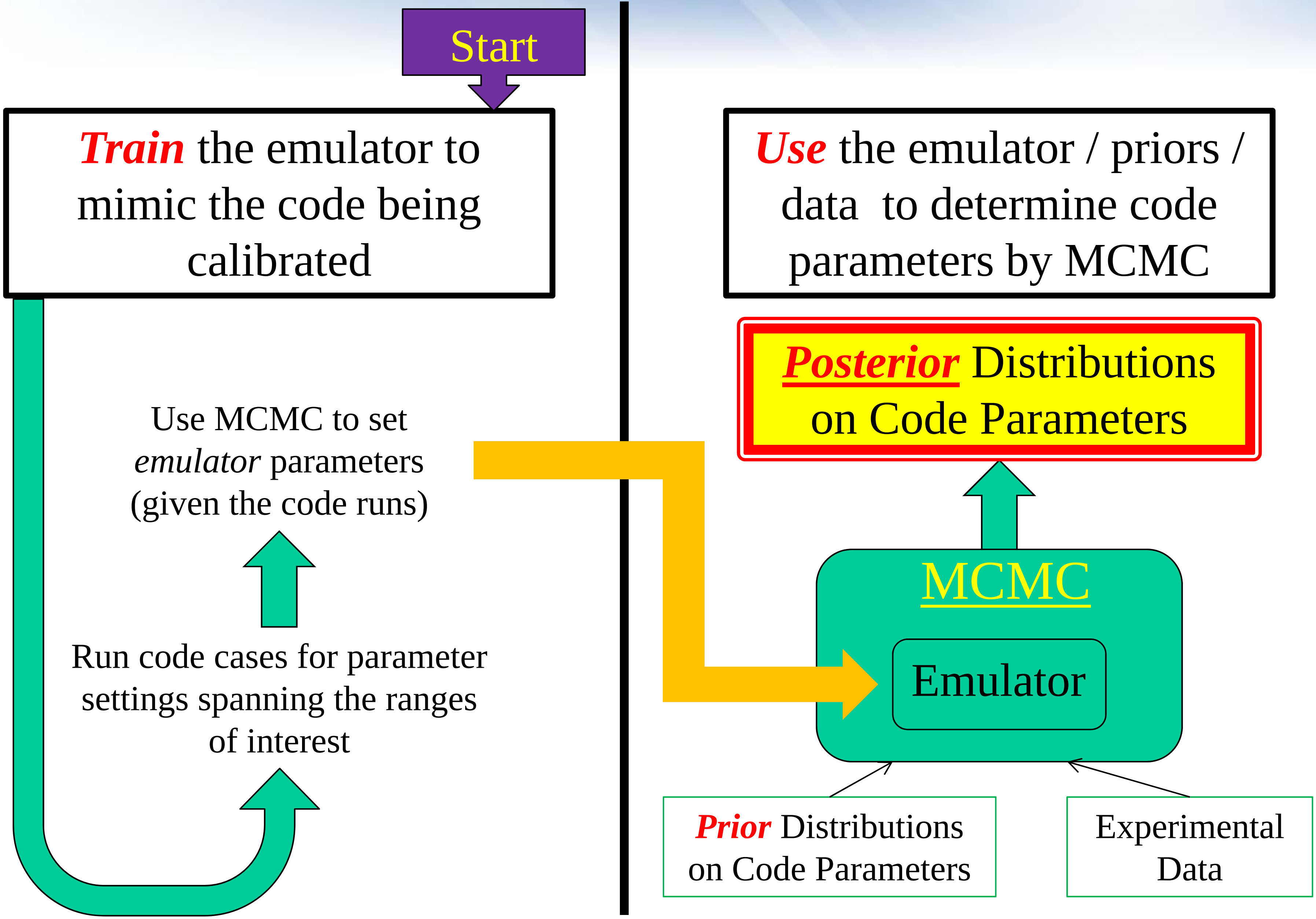
How do the output distributions compare to observational data?

Experimental data



Given the experimental data, what's the joint distribution of the inputs?

Task: Estimate physical model parameters, given data



Complicated thermal-hydraulic model with lots of uncertain parameters, "calibrated" with experimental data using a Bayesian Markov Chain Monte Carlo approach.

The posterior predictions nail the observations.

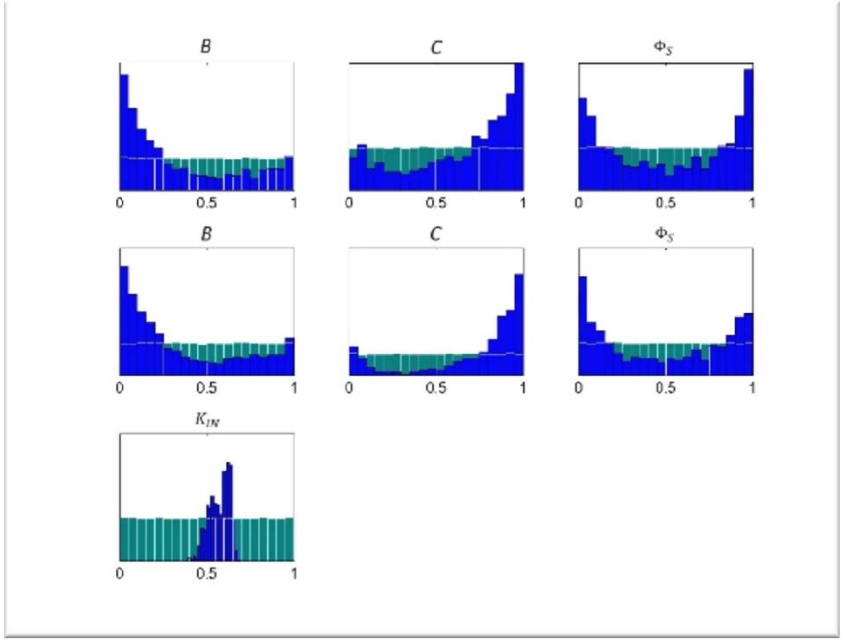


Fig. 9. IET only calibrated scaled posterior histograms

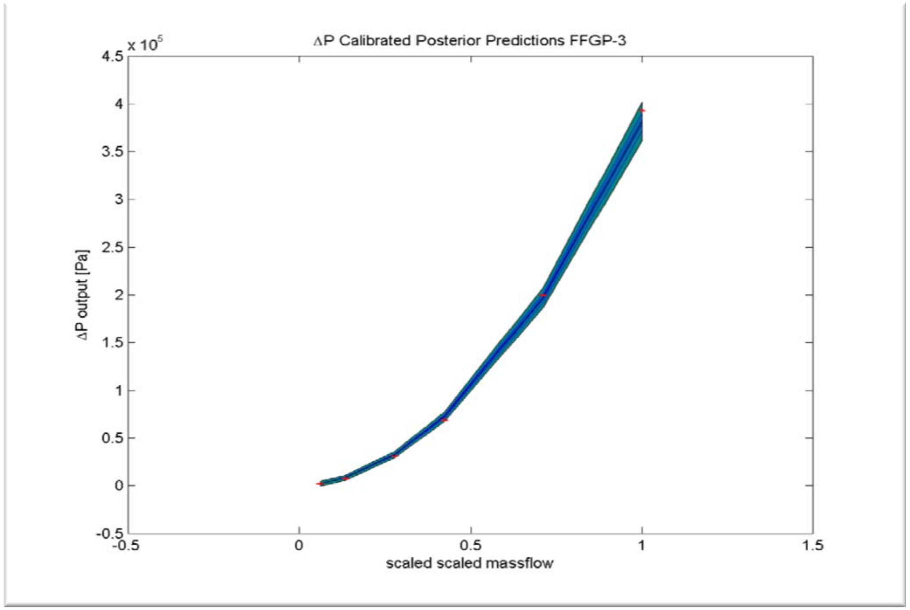


Fig. 8. IET calibrated posterior predictions relative to the "pseudo" data.

J.P. YURKO, *Uncertainty Quantification in Safety Codes Using a Bayesian Approach with Data from Separate and Integral Effect Tests*. Dissertation, MIT.

Cambridge, MA, 2014.

Population Variability

Original idea: Kaplan, S. On a ‘two-stage’ Bayesian procedure for determining failure rates. *IEEE Transactions on Power Apparatus and Systems*, 1983, **PAS-102,** 195–262.

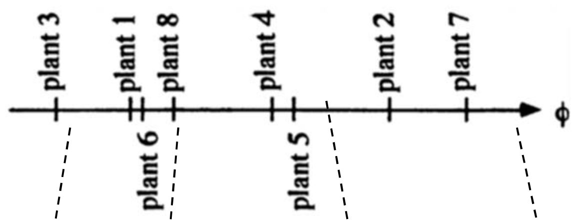


Fig. 4. Illustrative plot of plant-specific failure probabilities.

Bayesian parameter estimation in probabilistic risk assessment
Nathan O. Siu & Dana L. Kelly

Reliability Engineering and System Safety **62** (1998) 89–116
Published by Elsevier Science Limited

0951–8320/98/$19.00

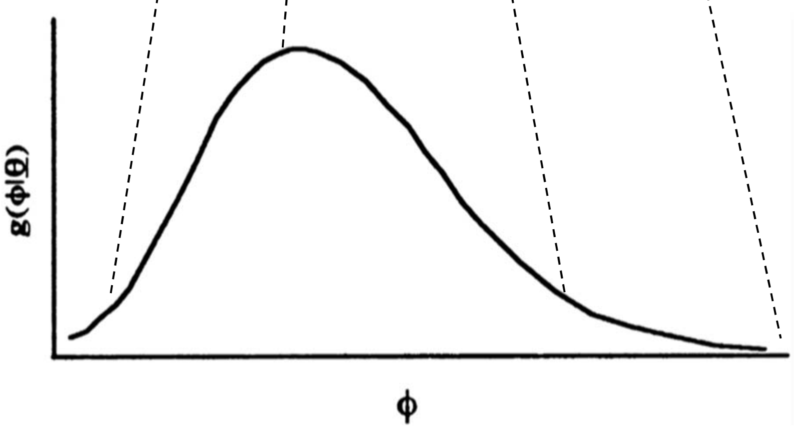


Fig. 5. Hypothetical population variability curve.

The general idea:
Instead of pooling performance data from different sources (e.g., facilities), as if everybody’s performance is the same: Develop a distribution expressing the variability in performance…

Population Variability (continued)

Fig. 5. Hypothetical population variability curve.

The general idea (continued):
… and use that distribution as a *prior* for the facility of current interest…
And update that prior with the data you have for the facility of current interest ("E") to get a posterior distribution for the facility of current interest

$$p\left(H_i \mid E\right) = P\left(H_i\right) \frac{p(E \mid H_i)}{p(E)},$$

$$p(E) = \sum_i p(E \mid H_i) p(H_i)$$

This approach makes essential use of the idea that it makes sense to think in terms of family characteristics: that other facilities' data carry implicit information about your facility.

General Principles:

- Strive to avoid the trap of understating uncertainty.
- Strive to make use of all available information that is legitimately applicable to the decision at hand.
- Maintain an essentially fallibilist posture with respect to analysis results.
- Be very careful about using the full standard Bayesian approach based on formulation and updating of an explicit prior.
  - If there is a lot of objective evidence to bring to bear, apply that evidence to a maximally ignorant prior, checking along the way to see whether the prior and the evidence are tugging the posterior in opposite directions.
  - "A lot of objective evidence" means "sufficient evidence that the posterior is reasonably insensitive to choice of prior."
  - If data and prior are incompatible, …

Summary

- It's extremely important to understand the uncertainties and what they do to the decision problem
- Bayes' theorem is a powerful tool for understanding the uncertainty, and for helping to figure out what to do in order to reduce it most effectively
  - Many problems in this arena might usefully map onto a "value of information" framework: what would it be worth to inspect / test / this pipeline?
  - *That question can be answered within classical decision analysis, if you understand your uncertainty.*
- A lot of theoretical capability has been developed.
- That capability has to be used with caution, because ...

$$p(H_i \mid E) = P(H_i)\frac{p(E \mid H_i)}{p(E)},$$

$$p(E) = \sum_i p(E \mid H_i)p(H_i)$$

…this stuff is all *user input*